Chapter 10

Ponds

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Ponds are familiar landscape features in all but the most arid regions of the world. In some areas, ponds are used to grow fish or crustaceans to generate profit from large-scale commercial aquaculture. In other places, ponds are used to grow fish for subsistence consumption at a small scale, often as part of farming systems that integrate plant and animal components (van der Zijpp *et al.* 2007). These noncommercial farms play a critical role in increasing food security and employment for the rural poor of developing countries (Edwards *et al.* 2002). Ponds often have multiple purposes, including potable water storage, irrigation water supply, livestock watering, storm-water retention, landscaping, and recreation. Although ponds can be used to grow aquatic plants, especially single-cell algae such as *Spirulina,* most ponds are used to grow aquatic animals, and such ponds will be the focus of this chapter. As well as being the most common aquaculture system in the world, ponds are also the most ancient way of growing fish, with origins before recorded history (McLarney 1984; Landau 1992). Pond aquaculture likely began as a natural extension of rice-field fisheries in Southeast Asia.

Ponds are commonly defined as small, confined bodies of standing water. This simple definition captures an important ecological feature of ponds. The phrase "of standing water" implies a long hydraulic residence time, which is the key functional attribute of a pond as an aquaculture system. An aquaculture pond can be defined more fully as an aquatic animal culture system where, by virtue of a long hydraulic residence time, suitable water quality for animal

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Aquaculture Production Systems, First Edition. Edited by James Tidwell.

production is controlled primarily by natural physical, chemical, and biological processes that occur within the water body. The significance of this definition is easier to understand by contrasting ponds with other common aquaculture systems. In flow-through (raceway) and net-pen systems, suitable water quality is maintained by continuous inflow of high-quality water; in recirculating aquaculture systems, water is reconditioned for use by pumping water through discrete water-treatment units (such as settling basins, biofilters, and gas reactors) that are separate from the fish-holding tank. The long hydraulic residence time in ponds also provides opportunity for considerable within-pond (autochthonous) food production for cultured animals, although the degree to which cultured animals rely on autochthonous food production for growth varies widely in different types of pond aquaculture.

The functionality of ponds as aquaculture systems is driven by solar energy, which regulates pond temperature and provides light for photosynthesis. Plants growing in the pond use specific wavelengths (colors) of light energy to synthesize cell components. During this complex process, plants assimilate carbon dioxide and mineral nutrients from the water, produce organic matter, and generate oxygen as a byproduct. Plant growth therefore provides three essential support functions in aquaculture ponds: (1) food for cultured animals, (2) oxygen to support life, and (3) treatment of wastes so that they do not accumulate to toxic levels.

At the most basic level, plants growing in ponds can provide all the resources needed to grow aquatic animals, with little reliance on support from ecosystems outside the pond. Millions of ponds and lakes throughout the world function in this way, supporting aquatic communities that thrive and persist without human intervention, powered only by sunlight falling upon the pond surface. However, energy available from sunlight impinging directly on the pond surface has a fixed maximum, which depends on latitude, time of year or day, and transparency of the atmosphere (generally as affected by cloud cover). Plant growth rate is ultimately limited by the finite energy available from sunlight, which in turn limits the capacity of a pond ecosystem to provide essential life-support functions. These limitations progressively shift from supplying sufficient food to supplying sufficient oxygen to removal of nitrogenous waste products as culturists try to achieve progressively greater crop yields (table 10.1).

Overcoming each limiting factor requires energy input from outside the pond to supplement services dependent on incident sunlight. Those inputs may be in the form of solar energy fixed as organic matter in other ecosystems and then transferred to a pond, or they may be direct inputs of industrial energy, mostly from fossil fuels. Examples of solar energy fixed in other ecosystems include production of plant feedstuffs (such as soybeans and corn) and production of marine plankton that are grazed by pelagic marine fish harvested for fish meal and fish oil. These allochthonous (from outside the system) materials can be formulated into feeds that are used to increase aquaculture production. Industrial energy inputs may include, for example, electricity to power aerators and water pumps to overcome limitations associated with oxygen supply and waste treatment.

Table 10.1 Aquaculture production at increasing levels of input for pond-raised channel catfish and tilapia. Modified from Boyd (1990) and Verdegem *et al.* (2006).

	Annual production (kg/ha)		
Management input	**Channel catfish**	**Tilapia**	**Limiting factor**
Stocking only	50–100	200–500	primary productivity
Stocking, fertilization	200–300	1,000–3,000	primary productivity
Stocking, fertilization, supplemental feeding	500–1,000	3,000–4,000	dissolved oxygen
Stocking, feeding	1,000–2,000	3,000–4,000	dissolved oxygen
Stocking, feeding, emergency aeration	4,000–6,000	4,000–6,000	dissolved oxygen
Stocking, feeding, continuous aeration	6,000–10,000	6,000–10,000	dissolved oxygen, metabolites
Stocking, feeding, continuous aeration, water exchange	10,000–20,000	15,000–35,000	metabolites
Stocking, feeding, continuous aeration, intensive mixing		20,000–100,000	metabolites, suspended solids

Aquaculture ponds may be filled with fresh, brackish, or salt water, and are usually constructed of soil, although some may be lined with plastic or other impervious materials to reduce water loss from seepage. Earthen ponds are typically shallow (<2 m), so interactions between soil and water have important effects on water quality. Most other aquaculture systems are constructed of inert materials (plastics or metals, for example) or water flows through the system so quickly that little time is afforded for interactions between soil and water. This attribute, where the container for water and cultured animals is an active biological and chemical component of the system, is unique to ponds among aquaculture systems.

Most ponds function simultaneously to confine cultured animals and treat wastes. In other words, animals roam free within a pond, usually dispersed at low densities compared to most other culture systems, and wastes produced by animals are treated or transformed by processes occurring in the same space. The animal confinement and waste treatment functions of ponds can be physically separated to achieve greater control over production. In such systems, space allocated to animal confinement is much less than space dedicated to waste treatment. Two "partitioned" variants of traditional ponds are described in other chapters of this book. Partitioned aquaculture systems are discussed in chapter 13 and in-pond raceways are discussed in chapter 15.

10.1 Species cultured

Nearly all types of aquatic animals can be grown in ponds but they are best suited for animals that tolerate a relatively wide range of environmental

conditions (Teichert-Coddington *et al.* 1997; LeFrancois *et al.* 2009). This is most obvious in the context of water temperature, the most important environmental factor affecting aquaculture production. Aquaculture ponds have a large ratio of surface area to volume and pond water has a long hydraulic residence time. Pond water temperature therefore closely follows local air temperature, which varies daily and seasonally. Further, because water has a large specific heat capacity, it is almost always impractical to heat or cool ponds to maintain optimum water temperature for culture. Lack of water temperature control has three important implications: (1) pond aquaculture is most common in tropical or subtropical regions that are characterized by long growing seasons; (2) species grown in temperate-region ponds must tolerate wide annual changes in water temperature, often ranging from near freezing to over 35°C; and (3) ponds are uncommon as culture systems in cold regions characterized by a very short growing season.

In addition to water temperature, other pond environmental variables also change over time because biological activity, which greatly influences pond water quality, varies in seasonal and diel cycles. Metabolic wastes are transformed and eliminated from pond water by natural microbial and physical processes, and the rates of those processes vary seasonally. Diel changes in water quality are especially evident for variables affected by photosynthesis and respiration. Dissolved oxygen concentration normally increases during the day and decreases at night; carbon dioxide concentration normally decreases during the day and increases at night. Carbon dioxide concentration controls pH, with greater values during the day and lower values at night. The amplitude of these fluctuations increases as a function of phytoplankton density, which changes in response to culture intensity. In aquaculture ponds operated at a high intensity, environmental conditions may vary from optimum to nearly lethal over time frames as short as hours. As with water temperature, most water quality variables in ponds are difficult, impractical, or expensive to control. One notable exception is dissolved oxygen supply, which is supplemented in some ponds with mechanical aerators. Because water quality varies greatly over short time frames in most ponds, the signature characteristic of animals most commonly cultured in ponds—such as carps, catfishes, tilapias, and penaeid shrimp—is that they are among the hardier species with respect to environmental tolerance.

Global aquaculture production data collected by the United Nations Food and Agriculture Organization are not classified by production system so it is difficult to precisely estimate production from ponds. Based upon the most likely culture system used for various species (FAO 2006b), it appears that approximately 32 million tonnes of fish and crustaceans were produced in ponds throughout the world in 2006. This represents about 60% of total aquaculture production (including plants), 70% of animal aquaculture, and 80% of finfish aquaculture. Most pond production in 2004 was attributable to freshwater cyprinid culture in China, India, and Southeast Asia (18 million tonnes), brackishwater culture of penaeid shrimp (2.5 million tonnes), freshwater tilapia culture (1.8 million tonnes), and brackishwater culture of milkfish (0.5 million tonnes).

In 2004, more than 310,000 tonnes of fish, crawfish, and marine shrimp were produced in 140,000 ha of ponds in the United States, which was about 65% of United States aquaculture production (USDA-NASS 2006). Almost 90% of the finfish produced in the United States were grown in ponds and nearly all were inland, freshwater ponds used to grow channel catfish (*Ictalurus punctatus*), crayfish (*Procambarus* spp.), bait and ornamental fish, and hybrid striped bass (*Morone saxatilis* × *M. chrysops*). A few hundred hectares of ponds located on the Texas coast are used to produce marine shrimp.

10.2 Pond types

Pond aquaculture comprises a wider range of culture species, environments, water sources, resource input levels, and environmental impacts than any other aquaculture system. Several classification systems can be used to simplify discussion and allow comparison among pond types. Some obvious classifications include ultimate use of product (foodfish, ornamental fish, sportfish, baitfish), species of animal (carp, catfish, shrimp), life stage (larval, fingerling, foodfish), salinity preference (freshwater, brackishwater, saltwater), and climatic or temperature regime (tropical, warmwater, coolwater, coldwater).

The type of plant that dominates the food web in a pond is another basis of classification. By far the most common are ponds where phytoplankton is the main plant type. Phytoplankton is an easily digestible form of plant protein and is an effective base for aquatic food chains. Phytoplankton also do not interfere with harvest of fish or crustaceans as do some other plant types. Some ponds are managed to favor attached algae or periphyton, which serves as the preferred natural food for fish such as tilapia (Azim *et al.* 2005). In parts of Southeast Asia, benthic attached algae growth is encouraged by filling brackishwater ponds to a shallow depth and then adding fertilizer. The community that develops with a mat of benthic algae serves as a food resource base for shrimp post-larvae following stocking. Intentional cultivation of aquatic macrophytes in aquaculture ponds is not common because they interfere with harvesting of cultured animals. However, in Louisiana, rice or naturally occurring aquatic macrophytes serve as the forage base of a detrital food web for the production of crayfish, which are harvested by trapping (McClain *et al.* 2007). Although aquaculture ponds are simple agroecosystems, they can be manipulated to expand the number of food niches available for exploitation by cultured animals.

Pond classification by hydrological type is instructive because water use, effluent volume and, to lesser degrees, water quality and effluent quality are impacted by pond hydrology. Various classifications and names are used to describe pond hydrological type; we will use the classification of Boyd and Tucker (1998).

Levee, or embankment, ponds (fig. 10.1) are the most common type used in aquaculture. Levee ponds are built on flat land by excavating a thin layer of soil from the pond bottom and using that soil to form levees or embankments around the pond perimeter. Sometimes fill is obtained by excavating a shallow trench

Figure 10.1 Embankment ponds at a large aquaculture research facility in Mississippi. Pond sizes range widely within this facility because the best size depends on research needs. Ponds in the foreground are approximately 4 ha, which is the average size of embankment ponds used in commercial catfish farming. Photograph courtesy of Danny Oberle, Mississippi State University.

from the internal periphery of the pond bottom, which results in the deepest part of the pond being just inside the toe of the levee. Catchment areas for rainfall and runoff are small, consisting only of the pond surface and the inside embankment slopes, so there must be a source of pumped water to fill ponds and maintain water levels during droughts. Water can be pumped from underground aquifers or nearby surface waters. In ponds sited within the intertidal zone of coastal areas, water can be added without pumping during high tides. Levee ponds can be built in almost any size or shape to accommodate landscape features. Large contiguous tracts of standard-shape (usually rectangular) ponds facilitate farm management.

Excavated ponds (fig. 10.2) are similar to embankment ponds, with respect to general construction and primary water source, but are usually smaller and the elevation of the pond bottom is further below the original ground level of embankment ponds. In areas with high water tables, excavated ponds may extend below the water table and be partially filled with groundwater inflow. Emptying excavated ponds may require pumping to lift water into drainage canals.

Watershed ponds (fig. 10.3) are built in hilly terrain by damming a temporary or permanent stream. The major source of water is runoff from the catchment basin above the dam, which can vary from constant inflow when a permanent stream is dammed to highly variable inflow when the watershed is small. Water level in ponds where the main source of water is runoff may vary greatly through the year and fall to critically low levels during dry seasons or droughts unless a supplemental source of pumped water is available.

The fourth pond type is a hybrid between embankment and watershed ponds. These ponds may have two or three sides consisting of embankments (actually

Figure 10.2 Excavated ponds (approximately 200 m^2) used to grow ornamental fish in Florida. Note the bird-exclusion netting and continuous diffused (bubbler) aeration to protect the valuable crop. Photograph courtesy of Dr. Jimmy Avery, Mississippi State University.

Figure 10.3 Watershed ponds used to grow channel catfish in Alabama. The pond in the foreground is approximately 8 ha. Photograph courtesy of Auburn University Department of Fisheries and Allied Aquacultures.

low dams) across a relatively small, shallow drainage basin. A significant amount of water may be obtained from runoff, but a source of pumped water also must be available because the catchment area above the pond is relatively small. Hybrid watershed-embankment ponds are built on land with gently rolling topography that is not ideally suited for embankment ponds or watershed ponds.

Embankment and excavated ponds have much less overflow than watershed ponds, with the overflow volume from hybrid ponds being intermediate. Also, the quality of effluents from watershed ponds may be affected (either positively or negatively) by upstream water quality, which is in turn affected by land-use practices in the watershed.

10.3 Water use

Compared to other culture systems, pond aquaculture uses relatively large volumes of water, and water availability constrains the location and size of pond aquaculture facilities. Adequate water must be available to fill ponds quickly and maintain the water level during prolonged periods of dry weather. Water use is also inextricably tied to waste discharge because water input and discharge are variables on opposite sides of the hydrological equation: increasing water input volume will increase water volume discharged.

Water budgets quantify inflows and outflows from ponds. Budgets include some or all of the following: inflows include precipitation, runoff, stream inflow, groundwater inflow, and regulated inflow; outflows are made up of evaporation and evapotranspiration, seepage, overflow, and regulated discharge. In the following section we briefly describe water budgets for ponds. Furthermore, Yoo and Boyd (1994) and Hargreaves *et al.* (2002) provide thorough discussions of the subject.

10.3.1 Sources

The main water sources for aquaculture ponds are precipitation, runoff from watersheds, and regulated additions of water from groundwater aquifers or surface water bodies (e.g., streams, reservoirs, and estuaries). Precipitation and runoff are the most important water sources for watershed ponds; precipitation and regulated inflows from groundwater or surface water are the primary water sources for embankment and excavated ponds.

Precipitation falling directly into a pond can be a significant source of water in some regions, although the frequency distribution of precipitation events varies greatly, even in humid climates, with many more precipitation events of low amount than of high amount. In the United States, the range of monthly rainfall among years is great, particularly during winter and early spring. Most tropical areas are characterized by distinct rainy and dry seasons, which have profound impacts on pond water budgets.

Watershed ponds are constructed to capture overland flow from the surrounding watershed, especially if ground or surface water availability is not reliable or predictable. Runoff volume depends on watershed characteristics, particularly slope, type and extent of vegetative cover, soil type, and antecedent soil moisture. Runoff is also a function of rainfall amount and intensity. Across the United States, runoff averages 28% of precipitation. In the southeast United States, overland flow is about 21 to 29% of rainfall from November to March, but very little runoff occurs from April to October (Yoo & Boyd 1994).

Embankment ponds have little area other than the pond surface to capture rainfall and therefore rely primarily on regulated inflows to initially fill ponds, to replace losses from evaporation and seepage, and to manage water quality with water exchange. The main sources of regulated inflow are surface water supplies and groundwater aquifers. Water from streams, rivers, or estuaries can be added by pumping or gravity flow as the sole water source or to supplement groundwater and runoff sources. Seasonal and year-to-year availability of some surface waters can be variable and availability often does not correspond to demand for pond aquaculture. For example, in the southern United States, peak stream discharge occurs during winter and early spring, yet the demand for water is greatest during summer. Surface waters are also undesirable because they are sources of contamination by wild fish, potential disease pathogens, agricultural pesticides, fertilizers, and sediment. Surface waters may also be regulated to limit withdrawals. Overall, groundwater is the preferred source of water for freshwater pond aquaculture. Groundwater is usually free of chemical and biological contaminants that may be present in surface waters and is usually not subject to the same fluctuations in availability as surface waters. However, groundwater aquifers recharge slowly and withdrawals that exceed recharge can reduce groundwater availability and lead to conflicts among users.

10.3.2 Losses

Water is lost from ponds by evaporation, seepage, and overflow that occur when inflows exceed pond water storage capacity. Losses from evaporation represent the only consumptive water use because this water is not available for downstream uses. In theory, water lost by seepage is available as groundwater and thus does not represent a consumptive use. Water is also lost when ponds are intentionally drawn down or drained for harvest, pond renovation, or in the case of crayfish culture, to stimulate crayfish burrowing and prepare ponds for planting vegetation. Water that overflows or is intentionally discharged is available for other purposes and thus does not represent consumptive use.

Evaporation is a function of atmospheric conditions that are beyond control of the culturist. However, seepage can be reduced by good site selection and pond construction practices. Overflow can also be minimized by maintaining water storage capacity and by not managing water quality with water exchange. Losses from intentional discharge can be minimized by reducing frequency of drawdowns or by pond draining.

10.3.3 Pond water use

Water use in aquaculture may be classified as either total or consumptive. Total water use is the sum of all inflows (precipitation, runoff, seepage inflow, and intentional additions) to production facilities. Depending on the type of culture system, a portion of the water entering the facility passes downstream in overflow or intentional discharge and is available for other purposes and thus is not consumed. For example, essentially all water flowing into flow-through systems is discharged, whereas some ponds have no discharge. Consumptive use is the water volume used in aquaculture that is subsequently unavailable for other purposes. Consumptive use includes water lost to evaporation from an aquaculture facility, and water removed in biomass of aquatic animals at harvest. Water in harvest biomass averages about 0.75 L/kg of animal produced, an insignificant quantity compared to losses from evaporation. Although groundwater withdrawals do not necessarily contribute to consumptive water use, groundwater withdrawals may contribute to aquifer depletion if withdrawals exceed recharge.

Total water use in ponds varies over a wider range than for any other aquaculture system, depending primarily on the frequency of intentional water exchange (flushing) and pond drawdowns or draining for harvest. Total water use ranges from less than 2 m^3/kg of aquaculture production in undrained ponds operated with no water exchange up to 80 m^3/kg for marine shrimp ponds operated with high (10 to 20% of pond volume) daily water exchange (table 10.2). For semi-intensive pond aquaculture, total water use typically ranges from 3 to 10 m^3/kg. To put these values in context, total water use is around 100 m^3/kg for trout raceways and 0.1 m^3/kg for recirculating systems.

Note that total water use to produce fish in extensively managed ponds is similar to that required in intensively managed ponds operated with water exchange (the top two entries in table 10.2, for example). Intensively managed

Table 10.2 Total water use in pond aquaculture. Conditions and values adapted from Phillips *et al.* (1991), Verdegem *et al.* (2006), Boyd (2005), and Tucker *et al.* (2008). Note the effects of culture intensity, species, and hydrological pond type.

Culture conditions	Total water use (m^3/kg)
Intensive shrimp, 20% daily water exchange	40–80
Extensive, warmwater fish	45
Intensive shrimp, Taiwan	29–43
Intensive tilapia, Taiwan	21
Semi-intensive shrimp, Taiwan	11–21
Carp polyculture, intensive, Israel	12
Channel catfish, watershed ponds, southeastern US	11
Warmwater fish, pellet-fed	9
Carp polyculture, semi-intensive, Israel	5
Channel catfish, embankment ponds, southeastern US	3–10
Warmwater fish, nighttime aeration	3–6
Low water exchange, sewage-fed, Thailand	1.5–2
Warmwater fish, intensive mixed ponds	0.4–1.6
Air-breathing catfish, Thailand	0.05–0.2

ponds with water exchange use large volumes of water to produce large crops. Extensive ponds use less water but produce proportionately smaller crops. This illustrates a common effect of culture intensity on resource use efficiency, with systems operating at an intermediate level of culture intensity using resources most efficiently.

Ponds in general have the greatest consumptive water use of all aquaculture systems because they have large surface areas for water loss from evaporation. Consumptive water use is typically less than 0.1 m^3/kg of aquaculture production in flow-through and water recirculating systems, but is 1 to 5 m^3/kg or more for aquaculture production in ponds, depending on climate. Water used for water exchange in shrimp ponds is pumped from bays or estuaries and discharged into the same water body, so only water lost to evaporation is used consumptively, but the supply of brackishwater is essentially limitless. In the past, fresh water was added to seawater to adjust salinity in some marine shrimp ponds operated with water exchange. In this case, the added fresh water was used consumptively because it was discharged to the marine environment and not available for other uses.

Although the consumptive use of water in pond aquaculture is relatively large, that use has high economic value as measured by the consumptive water value index (Boyd *et al.* 2007), which compares consumptive water use and gross economic value for crops per unit area. For example, in the southeastern United States, channel catfish aquaculture requires more water than irrigated cotton, corn, and soybeans, but an amount comparable to rice (50 to 100 cm/year). However, the economic value of water used for catfish aquaculture (about US\$1.00/m^3 of consumptive water use) is much greater than the value of water applied to other crops (less than US\$0.10/m^3). The consumptive use of water in other aquaculture systems is much less and the corresponding economic value of water use is much higher than for ponds. As examples, the consumptive water value index for trout grown in raceways is approximately US\$50/m^3 and for tilapia in cages is about US\$650/m^3 (Boyd *et al.* 2007).

10.4 Pond culture intensity and ecological services

The term *culture intensity* is used to classify agriculture systems based on crop yield per unit land or water area. When defined in that manner, culture intensity varies over at least three orders of magnitude for commonly used aquaculture production systems. At one extreme, water-recirculating systems are capable of annually producing 1 to 2 million kg of fish per hectare of culture unit. The same fish production in flow-through raceways requires about ten times more surface area, and production in ponds may require 1,000 times the area of recirculating systems. Fish production in recirculating systems is therefore considered more intensive than production in ponds. Culture intensity can also describe production characteristics within a production system type, which is especially common in describing production from ponds.

The concept of culture intensity not only includes consideration of relative crop yield but also the broader context of resource inputs. Combining contexts of

crop yield and resource use into the overall concept of culture intensity highlights the fact that differences in crop yields among aquaculture systems are not simply a function of systems with greater yields having inherently greater value than systems with lesser yields. Rather, a broader measure of culture intensity considers the extent to which the primary natural resources and ecological services needed to grow aquatic animals—food, life support, and waste treatment—are obtained from outside the culture facility.

The intensity of pond aquaculture—and therefore the degree to which pond aquaculture depends on external resources and services—varies over a wider range than other production systems. Yields in pond aquaculture vary over at least two orders of magnitude, from 200 kg/ha in lightly fertilized recreational sportfish ponds to more than 20,000 kg/ha in intensively managed cultures with feeding and continuous aeration. At the low end of the intensity spectrum, all food and oxygen needed to support fish growth is produced in the pond and most of the wastes produced during culture are retained within the pond, where they are removed or transformed by natural processes. At the other extreme, nearly all resources needed to grow animals in intensive pond systems are provided from ecosystems external to the pond. Animal growth is supported by large inputs of feeds manufactured from ingredients obtained from ecosystems outside the pond. Wastes resulting from feed inputs stimulate high rates of biological activity within the pond and natural supplies of dissolved oxygen are inadequate to meet the overall oxygen demand. At the upper limits of intensity, rates of natural processes within the pond become inadequate to remove all the wastes produced during culture and water exchange is used to eliminate excess organic matter or potentially toxic metabolites. When water is flushed from ponds to remove wastes, adjacent water bodies or land areas are used to treat or assimilate those wastes. Viewed in this manner, culture intensity is closely associated with the concept of ecological footprint, which is a tool for assessing the dependence of an activity on resources or services appropriated from other ecosystems. That is, the overall ecological footprint (which equals the facility area plus support area) of extensive pond aquaculture is small relative to intensive pond culture because land and water area outside the pond is used to provide the ecological services that support high levels of production.

In the next two sections, we describe food production and life-support processes in pond aquaculture. The important life-support processes in ponds are provision of dissolved oxygen and waste treatment. In each of the following sections, note how subsidies of external resources are increasingly needed to make high levels of production possible as culture intensity increases. This underlying theme will then be summarized in the section 10.7 "Land use and the ecological footprint of pond aquaculture."

10.5 Food in pond aquaculture

The fundamental goal of pond aquaculture is to manage a water body so that it will produce more aquatic animals than it would without management. To

enhance crop production, providing more food is essential. Food availability can be increased either by enhancing natural productivity within a pond or by providing supplemental food, often in the form of manufactured feed, from sources external to the pond.

10.5.1 Pond fertilization

Primary productivity (plant growth) is the base of the food web in extensive pond systems, but natural levels of primary productivity are usually inadequate to support high aquaculture yields. Primary productivity can be increased by fertilizing ponds with essential plant nutrients—predominantly nitrogen and phosphorus. The goal of a fertilization program is to increase production of natural foods that can be consumed directly or indirectly by cultured aquatic animals. These natural foods include phytoplankton, periphyton (attached algae), phytoplankton-derived detritus, algal-bacterial aggregates, zooplankton, and benthic invertebrates.

Greater food availability in fertilized ponds can increase aquaculture production by factors of five to ten, depending on the food habits of cultured animals and the efficiency of natural food use (table 10.1). For example, Nile tilapia (*Oreochromis niloticus*) responds well to pond fertilization because the fish grazes directly on phytoplankton and periphyton, as well as other natural foods such as detritus and zooplankton. Net fish yields of 10 to 20 kg/ha per day in fertilized tilapia ponds in the tropics are possible. In contrast, fish such as channel catfish are not able to feed directly on algae or other plants, feeding instead on secondary production of zooplankton, insects, and other herbivorous animals. The lower thermodynamic efficiency of animals feeding at higher trophic levels is a well-known ecological principle, implying that production of channel catfish, for example, will not respond to pond fertilization to the same degree as production of strictly herbivorous or omnivorous aquatic animals.

Aquaculture production in fertilized ponds can also be optimized by culturing in the same pond two or more species of animals with different food habits. This strategy, called polyculture, makes more efficient use of the variety of natural foods available in fertilized ponds. For example, a possible combination of fish might be silver carp (*Hypopthalmichthys molotrix*), grass carp (*Ctenopharyngodon idella*), and common carp (*Cyprinus carpio*). Silver carp feed in the water column by filtering plankton; grass carp are adapted to feed on aquatic macrophytes and added green fodders; and common carp are benthic omnivores that feed on detritus and benthic invertebrates. This combination makes efficient use of the different foods available in fertilized ponds. Net fish yields of 10 to 40 kg/ha per day are possible in fertilized polyculture ponds (Lin *et al.* 1997).

The best fertilization strategy maximizes profit, which may not necessarily correspond to maximum yield. The economics of fertilization (like that of other inputs to pond aquaculture systems) is subject to the Law of Diminishing Returns where, past some intermediate input level, each successive increment of an input results in progressively less output. The costs of a fertilization strategy include

unit costs of nutrients in a particular fertilizer and costs associated with transport, handling, and application. Furthermore, the opportunity cost of farm capital and labor must be considered.

Algae growth in aquaculture ponds is affected by temperature, light availability, and the rate of nutrient supply. Culturists have no practical control over temperature in ponds, but selecting sites in warm or tropical climates will favor algal growth. Typically, algal growth will double for every 10°C increase in temperature between 10 and 30°C. Fertilization when temperature is too low for phytoplankton growth can be counterproductive and favor growth of undesirable filamentous algae or rooted aquatic plants.

Ultimately, the availability of light limits primary productivity in fertilized ponds. Fertilization can increase algal density to the point where self-shading shifts the limitation of photosynthesis from nutrient supply to light. Availability of light for photosynthesis is reduced by algal and mineral turbidity and water color (staining). The efficiency of light use for photosynthesis can be improved by mixing ponds, which increases average light exposure experienced by phytoplankton. Mixing also increases the availability of nutrients recycled from the sediment.

Given the limited control over temperature and light availability in pond aquaculture, culturists justifiably focus on increasing the supply of nutrients required for plant growth. Algal growth is assumed to be limited by supply of the nutrient—or more broadly, the resource—that is most scarce relative to the requirement, a principle known as Liebig's Law of the Minimum. Nutrient limitation of algal growth must be seen in the context of nutrient requirements relative to the supply of that nutrient. When nutrient demand exceeds supply, nutrient limitation occurs. Of the approximately twenty elements needed for growth by aquatic plants and algae, carbon, nitrogen, and phosphorus are most likely to be in short supply, and, as a practical matter, it is only necessary to meet the needs for those three nutrients in a fertilization program.

Although carbon is the element required by algae in the greatest amount, its supply limits algal growth only in highly productive waters enriched with nitrogen and phosphorus or in waters of very low alkalinity. Dissolved carbon dioxide gas is the primary source of carbon for algal photosynthesis. The gas enters the water by diffusion from the atmosphere or is produced by respiration of pond organisms, including algae, microorganisms, and cultured animals. Many algae also use bicarbonate as a carbon source, either directly as the bicarbonate anion or indirectly when bicarbonate dehydrates to produce carbon dioxide. The water's carbonate-bicarbonate alkalinity system is therefore an important potential source of carbon for photosynthesis. In some cases, lack of a response to fertilization can be attributed to carbon limitation, and in those cases the response to fertilization can be improved with liming to maintain alkalinity greater than 20 to 30 mg/L as $CaCO_3$ (Boyd & Tucker 1998).

To describe nutrient dynamics in aquaculture ponds in the simplest terms, nitrogen cycling is dominated by biological processes and phosphorus cycling is dominated by physicochemical processes. Proportionally more nitrogen than phosphorus is recycled to the water column during the mineralization of nutrients

in algal detritus. The preferred form of inorganic nitrogen for algae is ammonia, although algae can take up nitrate if ammonia is absent. Ammonia is the form of nitrogen that increases in pond water with the addition of many common nitrogenous chemical fertilizers (e.g., urea, diammonium phosphate).

In comparison to inorganic nitrogen, inorganic phosphorus quickly becomes incorporated into the sediment in forms of variable availability, with most being tightly bound. Phosphorus solubility is affected by pH, especially in compounds with aluminum and calcium ions, and oxidation-reduction potential, which affects the solubility of phosphorus compounds with iron. Anaerobic conditions at the pond bottom can promote the release of iron-bound phosphorus from the sediment, a process called internal fertilization. Nutrient availability in the water column is enhanced by pond mixing or destratification and is restricted by thermal stratification. In general, ponds are sinks for nutrients, especially phosphorus, but nutrients can be recycled from the sediment to water from organic matter decomposition, diffusion from anaerobic sediment, and desorption during sediment resuspension.

Chemical fertilizers are manufactured in forms—including solid, liquid, instantly soluble, and controlled-release—that vary in solubility, nutrient availability, and cost. Organic fertilizers also vary widely in nutrient content and availability but are characteristically dilute sources of nutrients. Thus, much more organic fertilizers are required than chemical fertilizers to obtain a favorable algal growth response. The cost of organic fertilizers per unit nutrient is much greater than that of chemical fertilizers.

Organic fertilizers encompass a wide range of materials, including animal manure, green manure, fodders, composts, cereal grains, and seed meals. Organic fertilizers are especially important as a source of particulate organic matter for the production of zooplankton in fish nursery ponds (Anderson & Tave 1993). Organic fertilizers act to stimulate autotrophic (algae-based) and heterotrophic (detritus-based) food webs in aquaculture ponds.

Organic fertilizers have very different effects on water quality than do chemical fertilizers. Unlike chemical fertilizers, organic fertilizers decompose and exert an oxygen demand on pond water and also provide carbon dioxide for photosynthesis. Excessive organic loading can lead to oxygen depletion and organic matter accumulation on pond bottoms. Decomposition of organic fertilizers can also result in staining of water, thereby reducing light availability in the water column. In cases where visibility is limited by clay turbidity, organic fertilizers can increase light availability by serving as a coagulating agent.

A fixed-input fertilization strategy based on research is the most common fertilization practice, probably because it is the simplest approach. The selected rate is the input level that maximizes profit in controlled fertilization studies or field trials. Fixed fertilization rates are often adequate but do not account for variation in soils, water quality, and other site-specific characteristics. Fixed rates also do not account for changes in conditions during production and differences in pond-to-pond response, even for adjacent ponds. The differential response of ponds treated similarly is common. Understanding the pond characteristics and environmental factors that cause differential response to fertilization can

improve the efficiency of fertilizer use. Thus, as an alternative to a fixed-input fertilization strategy, fertilization rate can be based on pond-specific measurements made during the production cycle, including water and sediment analysis, computer modeling, or an algal bioassay that evaluates the response to nutrient enrichment of water samples (Knud-Hansen 1998). Fertilization programs based on pond-specific measurements of nutrients are complex, labor-intensive, difficult to interpret, and often not practical, cost-effective, or necessary.

Fertilization rates will depend on soil and water type but ultimately are a matter of cost-effectiveness. Recommended fixed fertilizer rates range from 10 to 30 kg N/ha per week, with lower rates in this range used when Secchi disk visibility is less than 20 cm. It is difficult to make specific recommendations about fertilization with phosphorus because availability is strongly affected by fertilization history. Recommended phosphorus fertilization rates range from 1 to 4 kg P/ha per week, with greater rates in this range appropriate for ponds with water of high hardness (>100 mg/L as $CaCO_3$). Phosphorus fertilization rates of 7 to 10 kg P/ha per week can be applied to the water of newly constructed ponds or ponds with clear water. Phosphorus fertilization rates can decrease over time as the capacity of the sediment to adsorb phosphorus decreases. Over time, the N:P ratio of fertilizer can be increased from one or two up to eight by reducing phosphorus input.

From the perspective algal growth requirements, providing frequent doses of fertilizer nutrients is best. The decision of fertilization frequency is based on fertilizer type and the opportunity cost of farm labor. For chemical fertilizers, a fertilization frequency of one application every one to two weeks is sufficient to obtain good response. For manures, daily application of low amounts of fertilizer is best to minimize the risk of oxygen depletion. Typically, chemical fertilizers are broadcast over the pond surface and the poor solubility of many chemical fertilizers can be improved by dissolving them in water before application. Chemical fertilizers can also be applied on platforms or in porous bags that cause the slow leaching of nutrients. Liquid fertilizers are denser than water and should be diluted in water before application.

Ultimately, decisions about fertilization are governed by economics, with costs of the material, transport, and handling part of the decision. Furthermore, the opportunity cost of farm capital and labor must be considered. Finally, the opportunity cost of applying an organic fertilizer to a pond or another crop in the farming system must be evaluated. Fertilizers and fertilization practices are described by Lin *et al.* (1997), Boyd and Tucker (1998), and Knud-Hansen (1998).

10.5.2 Ponds with feeding

Aquaculture yield in fertilized ponds is limited by primary productivity (which is ultimately limited by solar radiation) and by how efficiently the cultured animal uses primary productivity for growth. To increase aquaculture yield past that attainable in fertilized ponds, feed ingredients from outside the pond must be

obtained, formulated into a palatable and nutritious feed, and fed to cultured animals. Examples of commercial pond aquaculture relying on manufactured feeds are production of channel catfish in the southeastern United States and penaeid shrimp in tropical coastal zones. Carp aquaculture in Asian ponds, traditionally practiced as extensive culture in fertilized ponds, is increasingly dependent on manufactured feeds to support high levels of production.

Although carbon in ingredients used in manufactured feeds is ultimately traceable to carbon fixed in photosynthesis (as is the case with all foods), the difference between fed aquaculture systems and chemically fertilized ponds is, of course, that the plant growth that supports food webs in fertilized ponds occurs inside the pond, whereas the plant growth that supports animal growth in fed cultures occurs outside the pond. For example, most manufactured feeds are made primarily of terrestrial oilseeds or grains (soybeans, wheat, corn) and fish meal from small pelagic fish harvested from the sea.

The quality of feeds added to ponds varies greatly depending on availability of resources, the nutritional requirements of the cultured animal, and the economics of production. Inputs to some culture ponds consist of low-quality organic matter that might otherwise be considered a waste product, such as animal manures, bedding (litter), and the byproducts of processing agricultural plants. For the most part, little of the aquatic animal production in these ponds is derived from direct consumption of the added organic material because it is generally nutritionally inadequate, unpalatable, or too difficult to ingest to support high aquatic animal production through direct consumption. A more significant source of food in waste-fed ponds is derived via autotrophic and heterotrophic food webs stimulated by addition of organic materials. As such, ponds receiving low-quality organic materials are more properly classified as fertilized ponds rather than fed cultures.

Some animals can, however, efficiently use low-quality organic matter for growth and direct consumption of those materials may account for a large portion of the food consumed. Grass carp is the best example of a commonly cultured animal that grows efficiently on inputs of forages and grasses. Grass carp is the third most commonly cultured aquaculture species in the world, with nearly 4 million tonnes produced in 2004 (FAO 2006b). China is the leading producer of the fish. Most grass carp production relies on inputs of terrestrial or aquatic plants harvested from nearby land or water bodies and then processed to some degree (often by simply chopping into smaller pieces) and fed directly to fish in ponds or cages. Agricultural byproducts, such as leaves of corn, soybean, or other crops, are also used as food in grass carp cultures. Fecal wastes from grass carp then serve as a green manure that stimulates primary productivity when nutrients are released upon decomposition. Silver carp and common carp are often stocked in such ponds to exploit natural productivity enhanced by grass carp manure.

As culture intensity increases, from a nutritional standpoint, growth of cultured animals becomes limited first by the availability of dietary energy (De Silva & Anderson 1995). Therefore, providing supplemental inputs such as energy-rich cereal grains can complement natural foods and increase aquaculture

production beyond that obtained by fertilization. As culture intensity increases further, protein becomes the next nutritional factor to limit production.

Most fish and crustaceans grown in aquaculture cannot efficiently make direct use of low-quality organic matter or raw grains, so feeds are manufactured to be a source of concentrated nutrients with high-quality ingredients that are nutritious and highly digestible. High-quality manufactured feeds are expensive, and feed costs may constitute 30 to 60% or more of the overall variable costs of production.

The food web in ponds with feeding is more complicated than simply "animal eats feed." Even when cultured animals are fed a nutritionally complete feed to satiety, they also incidentally consume some of the variety of natural food organisms produced within the pond. Although consumption of natural food organisms is usually not expected to contribute to a significant proportion of the total yield of animals fed manufactured feeds, natural foods can supply vitamins, essential fatty acids, or trace minerals that are important to animal growth, especially when manufactured feeds are not nutritionally complete. In the case of fed penaeid shrimp ponds, direct consumption of feed by shrimp is inefficient and a surprisingly large fraction of added feed functions as an organic fertilizer, stimulating the production of various natural food items that are subsequently consumed by shrimp.

10.6 Life support in pond aquaculture

To maximize production potential and profitability, cultured animals must be grown in an environment conducive to good growth and health. In practice, the most important aspects of maintaining environmental quality in aquaculture are providing adequate dissolved oxygen and removing or transforming metabolic wastes produced during culture. Ponds have a surprisingly large inherent capacity for providing these life-support functions. In fact, the capacity of ponds to provide oxygen and assimilate wastes is a key part of the definition of "ponds," as explained in the introduction to this chapter.

The capacity of pond ecosystems to provide life-support services is, however, limited (Hargreaves & Tucker 2003). As culture intensity increases, so too does dependence on external subsidies of energy and other resources to maintain adequate environmental quality. Whether it is economically justified to supplement the natural life-support capacity of ponds depends on production goals and economics. Typically, the capacity of the pond ecosystem to provide adequate dissolved oxygen is the first life-support function to be exceeded, and it may be profitable to supplement the pond's naturally produced oxygen supply with mechanical aeration.

Further intensification of production will eventually be constrained by the waste assimilation capacity of the pond ecosystem. At that point, excess organic matter and nutrients must be removed by other means, such as exchanging degraded water with high-quality water, in a manner analogous to water exchange in flow-through systems and net pens, or by additional treatment. Water

exchange or additional treatment are rarely justified economically and, in the case of water exchange, may be regulated by laws. With the exception of supplementing dissolved oxygen supplies with mechanical aeration, a fundamental goal of most pond aquaculture is to operate within the pond's inherent capacity to provide life-support functions.

10.6.1 Dissolved oxygen

Of resources under the control of the culturist, availability of dissolved oxygen is the next factor to limit production in ponds after meeting food requirements of cultured animals. Two complimentary aspects of dissolved oxygen are important in pond aquaculture: (1) maintaining dissolved oxygen concentration above a minimum threshold for the cultured animal and (2) providing sufficient oxygen supply to meet overall respiratory demand of pond biota. The importance of the first goal is obvious because animals will die or grow poorly if the concentration falls to critical levels for a long duration. Oxygen supply is important because providing adequate oxygen to maintain aerobic conditions throughout the pond maximizes the waste treatment capacity of ponds. Supplying oxygen to the sediment is especially important because many of the waste-treatment processes in ponds occur at or near the sediment-water interface.

Oxygen is not very soluble in water and relatively small changes in its supply or demand can cause large differences in dissolved oxygen concentration. Non-managed ponds seldom experience episodes of low dissolved oxygen concentration unless the pond is built in an area with unusually fertile soils or receives runoff enriched with organic matter or nutrients. But when ponds are fertilized or receive additions of feed to increase aquaculture production, overall rates of plant growth (usually in the form of phytoplankton) and other biological processes increase. As phytoplankton biomass increases in response to greater inputs of plant nutrients, water column gross oxygen production during photosynthesis increases. However, oxygen uptake by overall community respiration also increases because the biomass of plants and bacteria in water and sediment is also greater. This causes wide fluctuations in dissolved oxygen concentration over a 24-hour period as oxygen is produced only during daylight. The magnitude of fluctuations in dissolved oxygen concentration increases as phytoplankton density increases in response to nutrient loading. If the biomass of phytoplankton and other organisms is too high, dissolved oxygen concentration often becomes critically low at night. Maintenance of dissolved oxygen concentration above a critical threshold, which is a characteristic of the species cultured, is best accomplished by mechanical aeration. Using water exchange is an ineffective and inefficient means of adding oxygen to pond water.

Note the relationship between pond culture intensity and source of dissolved oxygen: in low-intensity culture, dissolved oxygen is provided entirely by natural processes (passive diffusion from the atmosphere and photosynthesis in the water column). As culture intensity increases, rates of oxygen supply from natural sources become inadequate to meet overall respiratory demand and natural

supplies must be supplemented with mechanical aeration powered by energy from external sources. In the extreme, hard-bottom or lined ponds are aerated continuously with multiple aerators, which produces well-mixed conditions and provides nearly all the dissolved oxygen needed to support respiration of cultured animals and other pond biota.

10.6.1.1 Processes affecting dissolved oxygen concentration

The dissolved oxygen concentration measured at a particular time and place in a pond is the result of many simultaneous biological, chemical, and physical processes that produce or consume oxygen. The primary oxygen sources in most aquaculture ponds are photosynthesis by phytoplankton and gas transfer (diffusion) from the atmosphere. The primary sinks for oxygen include phytoplankton, zooplankton, and bacterial respiration in the water column, respiration of cultured animals, sediment oxygen uptake (which includes respiration of organisms in the sediment plus oxygen-consuming chemical reactions), and gas transfer from water to the atmosphere. Details of these processes, briefly summarized below, are discussed in Boyd and Tucker (1998).

Daily dissolved oxygen budgets in most aquaculture ponds are dominated by photosynthesis and respiration of phytoplankton. At low phytoplankton standing crops (typical of non-fertilized ponds, for example), adequate oxygen is produced during daytime photosynthesis to meet overall pond respiratory demand and dissolved oxygen concentration remains relatively high. As culture intensity increases, average phytoplankton standing crops increase in response to greater loading rates of nitrogen, phosphorus, and other plant nutrients from fertilization or feeding. The effect of increasing phytoplankton biomass on daily net oxygen production is shown in figure 10.4 for a hypothetical aquaculture pond.

The oxygen budget in figure 10.4 uses equations from Smith and Piedrahita (1988) for phytoplankton photosynthesis and respiration. Fish and sediment respiration were calculated for conditions typical of semi-intensive catfish ponds in midsummer. The most important point shown by this general model is that daily dissolved oxygen surpluses occur only at intermediate phytoplankton standing crops. When phytoplankton biomass is very low or very high, daily net oxygen deficits occur that must be offset with mechanical aeration to provide dissolved oxygen to keep the aquaculture crop alive. Daily oxygen deficits develop at low phytoplankton standing crops because inadequate plant biomass is present to produce oxygen in photosynthesis to offset community respiration. Deficits develop at high phytoplankton standing crops because the restricted availability of light caused by algal self-shading, and possibly other factors, increasingly constrains photosynthesis as phytoplankton standing crops increase, but phytoplankton respiration continues to increase as a direct function of algal biomass. Eventually, phytoplankton standing crops can become so great that solar radiation cannot support gross photosynthesis at rates that exceed overall community respiration. Past that point, daily net oxygen deficits occur.

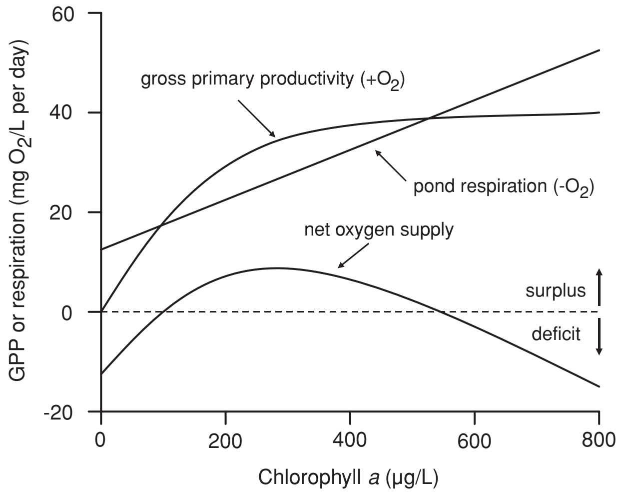

Figure 10.4 Dissolved oxygen budget for a hypothetical aquaculture pond as a function of phytoplankton biomass (chlorophyll *a* concentration is a common surrogate measure of algal biomass). In this budget, photosynthesis (gross primary productivity, GPP) by phytoplankton is the sole source of oxygen; respiration includes oxygen consumed by phytoplankton, fish, and sediment. The lower curved line is the net oxygen surplus or deficit calculated by subtracting respiration from gross primary productivity.

The relationship between phytoplankton density and net daily oxygen production shown in figure 10.4 assumes optimum conditions for algal photosynthesis. Conditions that reduce photosynthesis will reduce net oxygen production and may lead to critically low dissolved oxygen concentrations under conditions that otherwise would be safe. Examples of conditions that may reduce gross oxygen production and contribute to oxygen supply deficits include reduced solar radiation (prolonged cloudy weather, for example), reduced light penetration into the water from non-algal turbidity (from suspended clay particles, for example), and poisoning of phytoplankton with herbicides (Smith & Piedrahita 1988).

After plankton respiration, sediment respiration is the next largest sink for oxygen in most semi-intensive aquaculture ponds. Oxygen is consumed by the respiration of microorganisms and invertebrates living on or in the sediment and by chemical oxidation of reduced substances that diffuse from deeper sediment layers to the sediment surface. The sediment surface is the primary location for mineralization of organic matter, consisting mostly of detritus derived from phytoplankton and fish fecal solids that settle to the bottom. Nitrification of ammonia, a process that consumes oxygen, also occurs at the sediment surface.

Respiration of cultured animals is a function of biomass, animal size, water temperature, ambient dissolved oxygen concentration, time after feeding, and animal activity. Contrary to intuition, cultured animal respiration usually accounts for a relatively low proportion of overall oxygen use in ponds. For example, in semi-intensive catfish ponds, total respiration in ponds is partitioned among the water column (65%), sediment (20%), and fish (15%) (Steeby *et al.* 2004).

Gas transfer across the air-water interface can result in a gain or loss of dissolved oxygen from pond water, the direction of diffusion dependent on the difference between the dissolved oxygen concentration in pond water and the equilibrium (saturation) concentration. Diffusion can be an important source of oxygen when the deficit of dissolved oxygen concentration in pond water is large. Oxygen transfer across the air-water interface is a function of the difference in the partial pressure of oxygen in pond water and the atmosphere, turbulent mixing, and the pond surface area to volume ratio. The rate and direction of gas transfer therefore varies during the day and is at its maximum when the dissolved oxygen deficit (or surplus) is at maximum and when wind speed is high. Air to water oxygen transfer becomes of great practical importance when dissolved oxygen concentration falls to dangerously low levels because increasing oxygen transfer rate is the basis for managing dissolved oxygen supply with mechanical aerators. Mechanical aerators augment overall oxygen transfer rates by greatly increasing the air-water interfacial area and increasing turbulence within the pond.

10.6.1.2 Mechanical aeration

As pond aquaculture intensity increases, the imbalance between daily oxygen production and oxygen consumption increases, and aeration is needed more often and in greater amounts. This trend is illustrated by changes in aeration practices over the last fifty years of channel catfish farming. In the 1950s and early 1960s, catfish farming was practiced mainly to supply local markets as a more dependable and profitable alternative to wild-caught fish. Ponds without management were too unproductive to be profitable, even for these early low-intensity endeavors, and farmers sought to increase fish yield by fertilizing ponds or adding crude feeds. The risk of dissolved oxygen depletion increased as feeding and fertilization rates increased, and an early goal of pond management was to improve catfish production without degrading the environment to the point where aeration was needed. One of the first recommendations for channel catfish farming in the southeastern United States was to restrict maximum daily feeding rate to about 35 kg/ha to minimize the risk of oxygen depletion and the need for aeration.

In the 1960s and early 1970s, catfish farmers increased production by increasing fish stocking rates and feeding at correspondingly higher levels. They reached a point where supplemental aeration was occasionally needed to keep fish alive. Problems usually occurred late at night or around dawn, when night-time respiration had depleted the water of oxygen produced during daytime photosynthesis. Episodes of critically low dissolved oxygen concentrations were relatively rare, occurring only under unusual conditions such as prolonged periods of warm, cloudy weather or after sudden, unpredictable phytoplankton die-offs. Fish farmers often resorted to using irrigation pumps or other rudimentary equipment to oxygenate pond water.

Through the 1970s, catfish farmers continued to intensify production. Night-time oxygen depletions became more frequent and equipment was developed specifically for pond aeration. Aeration of large ponds required a relatively

Figure 10.5 A tractor-powered paddlewheel aerator. This paddlewheel directs water parallel to the pond embankment. Other designs push aerated water away and perpendicular to the embankment. Photograph courtesy of E. L. Torrans, United States Department of Agriculture.

large energy input, and early catfish pond aerators were powered by farm tractors (fig. 10.5). Farmers typically monitored dissolved oxygen concentration throughout the night and moved tractor-powered aerators to ponds where dissolved oxygen concentration was expected to decline to critical levels (usually 2 to 4 mg/L). This approach, called emergency aeration, made no attempt to manage dissolved oxygen levels throughout the pond. Rather, the goal was to provide a zone of well-oxygenated water near the aerator to support the respiratory needs of the fish biomass and operate the aerator until pond-wide dissolved oxygen concentration increased in daytime from algal photosynthesis.

Further intensification of catfish farming through the late 1970s and early 1980s was accompanied by a dramatic increase in the use of aeration. When average daily feeding rates exceeded 50 kg/ha through the growing season, often exceeding 100 kg/ha for long periods during summer, supplemental aeration was needed every night in most ponds. Initially, tractors were a convenient power source for aeration, but were expensive and inefficient. In the early 1980s, commercial catfish farmers shifted to permanently installed electric aerators (fig. 10.6). Electric aerators are much more efficient and currently the most common aeration device in most commercial pond aquaculture.

The evolution of catfish pond aeration practices illustrates the relationship among nutrient loading (intensification), oxygen budgets, and the need to supplement natural oxygen supplies. The frequency and amount of supplemental aeration also depends on cultured species. For example, penaeid shrimp live

Figure 10.6 A floating, electric paddlewheel aerator. Note the splash pattern and the zone of oxygenated water adjacent to the aerator. Photograph courtesy of E. L. Torrans, United States Department of Agriculture.

near the pond bottom and cannot quickly move large distances to find zones of aerated water. Shrimp ponds are therefore aerated for longer periods of time (many are aerated continuously) and with more aerator power per unit pond area than catfish ponds at equivalent nutrient loading rates. Aerators used in shrimp culture not only oxygenate water but also prevent stratification by mixing the water column to assure that oxygen supplied by aeration reaches the pond bottom where shrimp forage.

Aeration practices also depend on the goals of pond management and relative crop value. In some types of low-intensity aquaculture, such as sportfish ponds, the goal is to increase fish production through fertilization, but not to the point where phytoplankton and animal biomass becomes so great that additional management is needed to prevent oxygen-related fish kills. On the other hand, ornamental fish may be grown under relatively low-intensity conditions in ponds where episodes of critically low dissolved oxygen concentration are rare. However, the fish crop is so valuable that farmers may aerate ponds continuously to remove any risk of oxygen depletion from natural causes.

Aerators used in pond aquaculture are based on designs for similar equipment used in wastewater treatment. Aerators either splash water into the air (surface aerators) or release air bubbles under water to increase gas-water contact area. Surface aerators are most common in pond aquaculture. Aerators for large ponds are usually based on the paddlewheel design whereas impeller-type vertical pump aerators (fig. 10.7) are often used in small ponds. Aeration equipment and practices are reviewed by Boyd and Tucker (1998) and Boyd (1998).

Figure 10.7 An impeller-type vertical pump aerator. A submerged electric motor drives an impeller that throws water into the air. This type of aerator is especially suited for small ponds. Photograph courtesy of E. L. Torrans, United States Department of Agriculture.

Threshold minimum dissolved oxygen concentrations for warmwater fish (2 to 4 mg/L) are similar for good fish growth and survival and the maintenance of waste assimilation capacity. As such, pond aeration also serves to enhance other life support functions, such as waste nitrogen assimilation, in addition to the direct effect of providing dissolved oxygen to cultured animals. The direct value of aeration in preventing oxygen-related mortalities is obvious; however, the economic benefit of aeration to enhance the pond waste assimilation rate is unknown but likely not cost-effective. The most common aeration strategy in finfish ponds is to maintain a zone of aerated water near the aerator and not attempt to maintain dissolved oxygen concentration above a critical threshold throughout the pond to enhance waste assimilation capacity.

10.6.2 Waste treatment

Fish and crustaceans produce wastes as a byproduct of growth, and the amount of waste produced is proportional to animal biomass and feeding rate. Fertilization or feeding practices used to increase aquaculture production therefore increase the amounts of organic matter, solids, nitrogen, phosphorus, and other substances added to pond water.

Waste treatment in aquaculture has two distinct, but highly interrelated, functions. First, removal of metabolic wastes prevents degradation of the environment to the point where aquatic animal growth or health is negatively impacted. For example, bacteria that decompose organic materials added to ponds or produced during culture express an oxygen demand and compete with cultured animals for oxygen. Some substances, such as ammonia or nitrite, may accumulate and directly affect growth and health of cultured animals. Second, wastes produced during aquaculture also represent potential pollution if culture water is discharged from the facility. Regulatory constraints or negative impacts on the downstream environment can limit aquaculture production and profitability. As such, waste-treatment processes in aquaculture, whether inherent in the production system or as an adjunct to culture, reduce the pollution potential of aquaculture effluents.

10.6.2.1 Sources of nutrients and organic matter

The major nutrients applied to ponds in fertilizers are nitrogen and phosphorus. A portion of the fertilizer nutrients added to ponds is assimilated by plants, which then produce organic matter in photosynthesis. Plants are the base for the food web, eventually culminating in growth of cultured fish or crustaceans. Wastes are produced at each step in the food web because ecological efficiencies of nutrient use are not high, especially with natural foods. Even for fertilized ponds that are carefully managed, less than half the nitrogen and less than a quarter of the phosphorus applied as chemical fertilizer are eventually recovered in fish harvested. Efficiencies of carbon use are even lower, with less than 10% of the carbon fixed in photosynthesis recovered in fish harvested from fertilized ponds (Boyd & Tucker 1998). Differences between nutrient inputs (or production in the case of carbon) and amounts recovered in fish represent the waste load added to ponds.

Waste loads for ponds with feeding can be calculated by subtracting amounts in fish harvest from amounts in feed. Waste loads as percentages of feed inputs vary depending on species cultured, feed quality, and other factors, but using channel catfish as an example, about 80 to 90% of the dry matter and carbon, and 70 to 80% of the nitrogen and phosphorus in feeds is released to ponds as waste. Nutrients that are not assimilated stimulate high levels of organic matter production in photosynthesis, so overall loading of organic matter in ponds with feeding is much greater than indicated by simple mass balance. In one study (Boyd 1985), nutrients released during production of 1,000 kg of channel catfish supported production of 2,000 kg of dry matter in the form of phytoplankton.

Because large fractions of nutrient and organic matter input are not recovered in harvested animals, considerable quantities of waste are added to water in intensive pond aquaculture. Most waste nitrogen is excreted as ammonia through the gills, but some is excreted as organic nitrogen in fecal solids that are rapidly mineralized by pond bacteria to ammonia. In channel catfish ponds with a typical midsummer daily feeding rate of 100 kg/ha, more than 500 mg/m^2 of nitrogen are

added to ponds in the form of feed protein. Assuming 70% of nitrogen added to feed is excreted to the pond environment as ammonia, approximately 350 mg/m^2 per day (or 0.35 mg/L per day in a 1-m deep pond) is excreted by fish as waste. At that daily loading rate, ammonia should rapidly increase to levels that kill fish. However, total ammonia in catfish ponds is usually less than 1 to 2 mg N/L, even after many months of feeding. This illustrates a phenomenon common to all waste budgets in pond aquaculture; that is, observed concentration is always less than expected based on simple mass balance. The difference between observed levels of nutrients and organic matter and the amount expected based on mass balance is attributable to biological, chemical, and physical processes that transform and remove wastes from pond water. These processes are important because they maintain, at no direct economic cost to the farmer (other than that for supplemental aeration), adequate water quality for animal production and they reduce the pond's pollution potential. In fact, the widespread economic success of pond aquaculture can be attributed in large part to low production costs associated with the inherent waste assimilation capacity of ponds, despite the internalization of those costs, unlike more open production systems.

Qualitative fates and cycling of organic matter and nutrients in aquaculture ponds do not differ greatly from other shallow aquatic ecosystems, and detailed discussions of these processes can be found in any good limnology textbook (Scheffer 1998). Details of aquaculture pond ecology and nutrient cycling are also presented in Delincé (1992), Tucker (1996), and Boyd and Tucker (1998). The following briefly summarizes fates of organic matter, nitrogen, and phosphorus in pond water. These three variables have important implications for pond water quality and the environmental impacts of pond effluents.

10.6.2.2 Organic matter

In ponds with fertilization or feeding, the creation of "new" organic matter by algal photosynthesis far exceeds the amount added from solid fecal wastes or intentional additions of organic fertilizers. Organic matter loading from photosynthesis can be very large, with annual production of several thousand kilograms of organic solids per hectare in intensively managed ponds. In fact, sustainable operation of pond aquaculture is predicated in large measure on the capacity of the pond to remove the large amounts of organic matter produced during culture.

Some phytoplankton and other organic solids are consumed by zooplankton or other invertebrates, but most of the organic matter from phytoplankton biomass and solid fecal wastes is decomposed in the water column and at the sediment-water interface. Aquaculture ponds are shallow so most organic matter settles to the sediment before it is decomposed. The settled organic matter is readily decomposed because it consists of easily biodegradable organic matter in the form of dead phytoplankton, detritus of phytoplankton origin, or fecal solids. Water temperature and oxygen availability are the two major factors affecting rates of organic matter decomposition in ponds. Decomposition converts (mineralizes) the organic matter into inorganic components such as carbon

dioxide, ammonia, and orthophosphate, which may be recycled into new organic matter production when assimilated by phytoplankton. Organic matter decomposition also produces dissolved organic compounds that may serve as substrate for bacterial or fungal growth. All these processes occur continuously in a complex cycle of input, uptake, decomposition, reuse, and removal. When water is discharged from ponds, some fraction of the various forms of solid and dissolved organic matter is released to the downstream environment.

10.6.2.3 Nitrogen

Nitrogen is a major nutrient affecting productivity of aquatic ecosystems because it is an essential component of protein and other constituents of cellular protoplasm. Nitrogen is important in fertilized ponds because it is a key plant nutrient that may be in short supply relative to the amount needed for plant growth. In culture systems provided with manufactured feed, nitrogen is important as a constituent of feed protein and as a waste product of animal metabolism. Nitrogen in animal wastes may contribute to excessive phytoplankton abundance and may also lead to the accumulation of ammonia and nitrite, which can be toxic to aquatic animals. Waters discharged from ponds may also be enriched with inorganic and organic combined nitrogen and contribute to nutrient enrichment of receiving waters.

Nitrogen occurs in water as various inorganic compounds and myriad organic compounds. Transformations among the various forms of nitrogen constitute the nitrogen cycle. Most transformations are biochemical oxidation-reduction reactions that are strongly interdependent, with rates of one process sometimes limited by the rate of substrate formation in a preceding process. For example, rates of denitrification in aquaculture ponds are often constrained by the rate at which nitrate (the substrate for denitrification) is produced by nitrification.

Variable but relatively small amounts of nitrogen enter the aquatic nitrogen cycle via biological nitrogen fixation by aquatic bacteria or blue-green algae. Fertilizers or feed accounts for most of the nitrogen input to aquaculture ponds. In fertilized ponds, nitrogen is added as chemical fertilizers or in nitrogen-rich organic materials. In fertilized ponds managed for high fish production from algal-based food webs, daily nitrogen input may exceed 400 mg/m^2. In ponds with feeding, almost all nitrogen originates from feed protein. As a typical value, about 25% of the feed nitrogen is recovered in fish production or, conversely, about 75% of the nitrogen in feed is released to pond water as waste from fish. Roughly 80% of the waste nitrogen in ponds with feeding enters the pond as ammonia, the primary nitrogenous waste product excreted by aquatic animals from the gills. Nitrogen also enters the water in fecal solids and uneaten feeds, but ammonia is quickly liberated when those materials decompose. Assuming a 25% retention of feed nitrogen and 30% protein in the feed, total waste nitrogen input to the pond water will be about 36 mg/kg of feed. At a feeding rate of 100 kg of feed/ha per day, a typical summertime feeding rate used in channel catfish culture in the southeastern United States, daily nitrogen loading would be 360 mg/m^2.

Decomposition of dead phytoplankton cells, fish fecal solids, uneaten feed, and other organic material releases ammonia. Some decomposition occurs in the water column but most takes place in the surface layer of pond sediment. The rate of ammonia production from organic matter mineralization depends on temperature, oxygen availability, pH, and the quantity and quality of organic matter. Some nitrogen-containing organic material accumulates in sediments but most is quickly decomposed and nitrogen is recycled to the water column. Ammonia recycled from organic matter decomposition in pond sediments accounts for 25 to 33% of the total ammonia input to water of catfish ponds (Hargreaves 1997), with fish excretion accounting for the balance.

Uptake by phytoplankton is the main sink for most combined inorganic nitrogen in aquaculture ponds. Rates of algal nitrogen assimilation are roughly proportional to rates of net photosynthesis, so factors affecting plant growth directly affect nitrogen assimilation. For instance, nitrogen uptake is reduced when water temperature is low, during periods of low sunlight intensity, or when the availability of some other nutrient limits plant growth. The magnitude of average rates of nitrogen assimilation by phytoplankton can be estimated by assuming that phytoplankton assimilate nitrogen in a fixed proportion to carbon. The so-called Redfield ratio of C:N:P in “average” phytoplankton tissue is 42:7:1 by weight. Daily net carbon fixation rates range from less than 0.5 to over 5 g/m^2 in semi-intensive aquaculture ponds, which corresponds to daily nitrogen assimilation rates of less than 80 to over 800 mg/m^2. Most of the ammonia produced from fish excretion and organic matter mineralization is assimilated by phytoplankton. The continuous recycling of nitrogen through the processes of phytoplankton uptake, cell death, mineralization of organic nitrogen, and re-assimilation by phytoplankton is an important feature of nitrogen dynamics in aquaculture ponds.

Ammonia from fish excretion or organic matter mineralization may also be adsorbed as ammonium ion by clays and organic colloids in pond bottom soils, volatilized into the atmosphere as ammonia gas, or nitrified by bacteria to nitrate. Quantitatively nitrification is second to phytoplankton uptake as a major sink for ammonia. Nitrification is the two-step transformation of ammonia to nitrite and then nitrate by chemoautotrophic bacteria. Nitrification rates are controlled by water temperature, oxygen availability, pH, and ammonia concentration. Nitrifying bacteria are strictly aerobic and rates of nitrification drop dramatically when dissolved oxygen level falls below 1 to 2 mg/L. Nitrification occurs over a wide temperature and pH range but optimum conditions are 25 to 35°C and pH 7 to 8.5. Nitrifiers tend to colonize surfaces, and highest rates occur at aerobic, sediment-water interfaces. Few direct measurements of nitrification in ponds have been made, but estimated rates range from 0 to 150 mg N/m^2 per day, with most estimates ranging from 25 to 50 mg N/m^2 per day (Hargreaves 1998).

Denitrification of the nitrate produced in nitrification is the main process by which nitrogen is lost from aquaculture ponds. Denitrification is the production of nitrogen gas by common heterotrophic bacteria that use nitrate or other oxidized forms of nitrogen, rather than oxygen, as terminal electron acceptors in respiration. Denitrification is an anaerobic process so it occurs primarily in

pond sediments just below the thin layer of oxidized surface sediment. The denitrification potential of aquaculture ponds is great because the volume of anaerobic sediment is large. The rate of denitrification depends on the availability of nitrate, so the process is tightly coupled with nitrification, which is the process by which nitrate is generated in aquaculture ponds. The coupling of these two processes—one aerobic and the other anaerobic—is ultimately dependent on oxygen supply because the rate-limiting step is the production of nitrate from nitrification.

Un-ionized ammonia and nitrite are potentially toxic to some aquatic animals and the risk associated with these two toxicants increases as culture intensity increases. In low-intensity pond aquaculture, nitrogen loading rates are low and problems with accumulation of ammonia or nitrite are extremely rare. In intensive culture, nitrogen loading rates from manufactured feeds are high, and at any one time large quantities of nitrogenous compounds are in flux among the various nitrogen cycle components. Under these conditions, relatively minor changes in process rates can result in accumulation of potentially toxic intermediate products (Hargreaves and Tucker 1996; 2005). For example, most of the ammonia excreted by fish is quickly detoxified when phytoplankton assimilate and incorporate ammonia into algal proteins. Ammonia will accumulate when rates of phytoplankton uptake are reduced, which may occur during prolonged cloudy weather, with herbicide use, or following naturally occurring algal die-offs. Likewise, nitrite, which is an intermediate in the two-step process of nitrification, may accumulate when the rate of the first nitrification step exceeds that of the second step. In both examples, the amount of reaction substrate (ammonia in the first example, nitrite in the second) that may accumulate is greater when the overall nitrogen loading rate to the pond is high.

Treating pond water to remove ammonia is difficult because large volumes of water are involved. Various treatments, some based on accelerating natural processes, have been proposed but most either do not work or are too expensive (Hargreaves & Tucker 2004). Ammonia can be removed by exchanging water and this is commonly practiced in some pond cultures. Water exchange may be continuous or occasional, such as whenever the pond manager feels that fish health is threatened. The need for water exchange and the efficacy of the practice as an ammonia-removal strategy is debatable in most pond aquaculture, particularly if ponds are large and water exchange rates are low (less than 10 to 20% per day). Moreover, if frequent water exchange is required to maintain ammonia concentration at a nonthreatening level, it is a clear indicator that the waste assimilation capacity of the pond has been exceeded. However, practicing water exchange to reduce phytoplankton density to the intermediate levels that maximize algal growth and ammonia uptake may be an effective control strategy.

In pond aquaculture, as defined here, the key to ammonia management is to minimize the probability of accumulation to toxic levels by operating within the assimilative capacity of the pond ecosystem. If ammonia concentration is routinely high in fertilized ponds, nitrogen is being supplied in excess of requirements for algal growth, which is wasteful of fertilizer and money. In ponds receiving feed, the risk of ammonia toxicity is reduced by using moderate stocking and feeding rates and using high-quality feeds and good feeding practices to

maximize nitrogen retention by the cultured animals. Other than these general rules and using experience to empirically determine the pond's assimilative capacity, it is difficult to precisely define nitrogen loading limits for ponds. As a rough estimate, however, the nitrogen assimilative capacity of a pond is roughly equivalent to the average rate of nitrogen uptake by phytoplankton. Nitrogen uptake rates vary from day to day, but a reasonable average daily uptake rate for warm, shallow, unmixed ponds is in the range of 300 to 500 mg/m^2. This corresponds to the amount of nitrogen excreted by fish when daily feeding rates for high-quality feed are in the range of 80 to 140 kg/ha. Algal nitrogen assimilative capacity must be increased (as it is in the partitioned aquaculture system; see chapter 13) if greater feeding rates are sustained over long periods.

Nitrite causes methemoglobinemia in some fish, which is a condition where nitrite enters the bloodstream across the gills and oxidizes iron in hemoglobin to the ferric state. Oxidized hemoglobin, called methemoglobin, is incapable of reversibly binding with oxygen and causes a functional anemia that puts fish at risk of hypoxia. Ictalurid catfish, salmonids, carps, and tilapias are especially sensitive to nitrite toxicosis (Tomasso 1994).

Nitrite accumulation in ponds is highly sporadic and appears to be most common in warm-temperate regions with pronounced seasonal changes in water temperature and solar radiation. In those regions, nitrite concentration in intensive aquaculture ponds shows a bimodal pattern, with maximum concentrations in spring and autumn. A model of nitrogen dynamics in catfish ponds (Hargreaves 1997) indicates that nitrification rate (and therefore the rate at which nitrite is produced) is a function of ammonia concentration and water temperature. During summer, nitrification rate is low despite favorable temperature because phytoplankton are better competitors for ammonia than nitrifying bacteria, and the low ammonia substrate concentration limits nitrification. In winter, nitrification substrate is not limiting because phytoplankton growth is slow under conditions of low light and cold water temperature, and ammonia concentration is correspondingly high. However, wintertime nitrification rates are slow because low temperature restricts microbial activity. Nitrite therefore accumulates when nitrification rates are maximum, which occurs at intermediate values of temperature and ammonia concentration, during spring and autumn.

Similar to considerations associated with the control of ammonia, removal of nitrite from large ponds is not practical. Fortunately there is an inexpensive treatment that protects nitrite-sensitive fish from toxicosis. Chloride is a competitive inhibitor of gill lamellar uptake of nitrite in nitrite-sensitive fish. Adding common salt to pond water to increase chloride concentration can prevent nitrite toxicosis. The required amount of chloride depends on the highest expected nitrite concentration and the fish species cultured. In channel catfish culture, where nitrite toxicosis is a significant potential problem, salt is routinely added so that the chloride concentration is at least thirty times the highest expected nitrite-nitrogen concentration. Typically salt is added to catfish ponds to maintain a chloride concentration of about 100 mg/L, which protects fish from all but the most extreme episodes of nitrite accumulation. Salt treatment is long-lasting because chloride is lost from ponds only during overflow associated with excessive rains, intentional water exchange, or pond draining.

10.6.2.4 Phosphorus

Phosphorus is a key metabolic nutrient that is available in relatively small amounts in most natural surface waters. The supply of phosphorus therefore regulates primary productivity in many natural waters. It is the key nutrient, with nitrogen, in pond fertilizers. Phosphorus is also important because aquaculture pond water is often enriched with phosphorus relative to natural waters and the discharge of pond water can increase the phosphorus concentration of receiving waters, potentially leading to eutrophication.

Fertilizer or feed accounts for virtually all phosphorus inputs to aquaculture ponds. Phosphorus may be added to ponds in water used for filling or water exchange, but amounts added are usually small unless the water supply is polluted or otherwise enriched with phosphorus. In ponds receiving applications of manufactured feeds, about 65 to 75% of ingested phosphorus is excreted, primarily as particulate fecal solids.

Unlike the nitrogen cycle, with many forms of inorganic nitrogen, the phosphorus cycle has one main form of inorganic phosphorus, called orthophosphate. Orthophosphate is formed when phosphorus fertilizers dissolve in pond water and released when organic compounds such as fish fecal solids and dead phytoplankton cells decompose. Much of the phosphorus in phytoplankton cells and organic detritus settles to the pond bottom before the opportunity for bacterial degradation and release of orthophosphate into the water column.

The ultimate fate of most phosphorus added to ponds is accumulation in pond sediment through chemical reactions with sediment minerals that render phosphorus unavailable for algal growth. The net movement of phosphorus from water column to sediment is, in fact, the major feature of the phosphorus cycle in aquaculture ponds. Depending on soil type and soil pH, phosphorus may be strongly bound as iron and aluminum phosphates in low pH pond sediments or calcium phosphates in sediments of higher pH. The continuous loss of phosphorus from the water column and accumulation in the sediment is the primary reason why phosphorus is usually the first limiting factor for phytoplankton growth, necessitating multiple ongoing additions of phosphorus to maintain high rates of primary productivity. Phosphorus accumulation in sediment is also important as a mechanism that reduces the potential impact of pond effluent on receiving streams. Water released from ponds always contains far less phosphorus than the amount added in feeds or fertilizer because nearly all the phosphorus input is retained in pond sediment. Detailed and quantitative discussion of this topic can be found in Boyd (1995).

10.7 Land use and the ecological footprint of pond aquaculture

Ponds use large areas of land to produce aquaculture crops, requiring orders of magnitude more facility area than flow-through or recirculating aquaculture systems. In that regard, ponds might be perceived as inefficient systems for producing food. However, as discussed in the section on culture intensity, land use in aquaculture is more complicated than simply accounting for facility area.

Aquaculture, as with agriculture generally, usually relies on additional area to provide ecosystem support or service functions. The overall land or sea area occupied by the facility plus that needed to provide all resources to grow a crop is called the ecological footprint. In aquaculture, the overall footprint includes areas for the facility, food production, and life support (which includes oxygen supply and waste treatment). Footprints may also include ecosystem requirements for other services, such as freshwater supply, forest or ocean area for carbon dioxide sequestration, and, for some systems, nursery areas used to produce seedstock or brood animals. As the term implies, the concept of ecological footprint focuses on requirements for land area, but the analysis can also apply to requirements and flows of energy and materials through the larger system that includes fish production and ecosystem support.

Fundamental thermodynamic principles dictate that the need for external ecosystem support increases as culture intensity (expressed as crop yield per unit area) increases. That is, low intensity culture systems have a low ratio of total support area to facility area whereas high-intensity systems require large areas external to the facility to support high levels of aquaculture production. For example, much of the ecosystem support for extensive pond aquaculture is inherent in the system. Traditional aquaculture ponds used in Chinese carp polyculture function not only to confine fish, but also to provide an internal area for food production, oxygen production, and waste treatment. Such systems may have ratios of support area to facility area that approach one. Or, stated another way, the ecological footprint is approximately equal to facility area. On the other hand, some aquaculture systems function only to confine the crop. Food for the confined animals is produced in external ecosystems and wastes are exported and treated outside the facility. In other words, the footprint of those systems is much larger than the facility area.

When considering the total ecosystem area needed to support a certain level of aquaculture production, the apparent differences in culture intensity based on yield per unit area nearly disappear. Although ponds require hundreds or thousands of times the facility area as other systems, those other systems rely on hundreds or thousands of times the external ecosystem area to provide food and waste treatment compared with ponds.

10.7.1 The footprint of food production

Most global aquaculture production depends on plant photosynthesis either within the culture unit (ponds) or in adjacent waters (open-water molluscan shellfish culture) to produce most of the food that supports animal growth. In ponds managed for autochthonous food production, aquaculture yield is limited by primary productivity, which in turn is ultimately limited by the amount of solar radiation that the culture unit receives. Such ponds are usually fertilized with plant nutrients to make the best use of incident solar radiation and are often stocked with two or more herbivorous and omnivorous species to make efficient use of the variety of available natural foods.

Annual yield of herbivorous or omnivorous fish can be quite impressive (3,000 to 10,000 kg/ha, or more) in fertilized ponds. To increase aquaculture productivity past that achievable in systems dependent only on autochthonous primary productivity, food produced outside the culture system must be imported. In some systems, that food may be low-quality organic matter that might otherwise be considered a waste, such as agricultural byproducts or livestock manures. In many aquaculture systems worldwide—and in nearly all commercial systems in the United States—allochthonous organic matter added to increase productivity consists of manufactured feeds made from plant (soybean and corn, for example) and animal (usually fish) meals. Production of terrestrial feedstuffs requires agricultural land, and production of fish meal and oil requires an area of marine ecosystems to produce small pelagic fish.

The ratio of supporting food production area to aquaculture facility area varies over four orders of magnitude depending on culture system, type of food, and feed composition. Carp, tilapia, and other fish at lower trophic levels can be grown in ponds fertilized with agricultural wastes or byproducts and do not require external ecosystem area for food production. Those systems have a value of around one for the ratio of ecosystem support to facility area. Growing omnivorous species like channel catfish in ponds appropriates an area for procurement of feedstuffs that is approximately ten times the area of the pond (recalculated from Boyd *et al.* 2007 using additional data on ecosystem area needed to procure fish meal). Intensive net-pen culture of carnivorous fish, such as salmon, requires an ecosystem support area for food production that is more than 10,000 times the area of the culture system (Folke *et al.* 1998). For aquatic animals that are fed, the ecological footprint for food production dominates the total footprint and the total footprint for a given level of fish production is similar among culture systems.

10.7.2 The footprint of life support

Every culture system must provide an environment conducive to growth and survival of cultured animals. Maintaining environmental quality within tolerance limits has two interrelated goals: providing oxygen and providing a mechanism to maintain concentrations of potentially toxic metabolites below some threshold. Providing oxygen sustains metabolism of cultured animals and enhances waste assimilation in ponds. Depending on culture intensity, life support services are provided to a variable degree by natural processes within the pond. As culture intensity increases, life support is increasingly dependent on biophysical resources and ecological services from outside the pond.

10.7.2.1 Dissolved oxygen

Solar radiation entering the water column provides energy to drive photosynthesis, producing oxygen as a byproduct. In extensive pond aquaculture, dissolved oxygen needed to sustain the aquaculture crop is produced within the pond.

The footprint of oxygen production therefore equals the facility footprint. Past that point, expressing external ecosystem support on an areal basis is inconvenient when speaking of operating inputs such as aeration, which are more intuitively (and commonly) expressed in energy units, such as kilowatt-hours (or kilojoules) of industrial energy input per kilogram of production. Expressed in this manner, no input of industrial energy for aeration is necessary for extensive systems where photosynthesis and gas transfer from the atmosphere supply all the dissolved oxygen.

Intensification of pond aquaculture results in greater biological activity, and gross daily oxygen production is often less than overall community respiration. The daily net oxygen deficit must be offset by mechanical aeration, which is an energy-intensive process. Typically, as culture intensity increases, aeration is needed for longer periods each day and higher-power aerators (or more aerator units) are needed to provide enough oxygen to offset the supply deficit. Overall energy inputs for aeration increase dramatically as production intensity increases or for animals such as shrimp that require more aeration than finfish. For example, catfish ponds in the southeastern United States may be aerated for 1,200 hours per year (about 6 hours per night over the 200-day warm-weather growing season). The total nominal power rating of the aerator motors divided by pond area averages about 1 kW/ha. If net fish production is 5,000 kg/ha, the industrial energy input for aeration is approximately 0.24 kW-hours/kg of fish produced (860 kJ/kg). Marine shrimp ponds are often aerated continuously and with more aerator power per unit pond area than catfish ponds. In contrast to catfish ponds, which may be aerated with 1 to 2 kW/ha, shrimp ponds may be aerated with as much as 10 to 20 kW/ha (Boyd 1998). If 10 kW/ha of continuously operated aeration will support a standing crop of 6,500 kg/ha of shrimp (Peterson *et al.* 2001) and two 150-day crops of shrimp are produced annually, then the industrial energy input for aeration is approximately 5.5 kW-hours/kg of shrimp produced (20,000 kJ/kg), or more than twenty times the energy input per unit production for catfish.

Although energy expended for aeration represents a significant operating cost in intensive pond aquaculture, it is much less than the energy required to produce or obtain feedstuffs and process them into feeds. The energy input associated with catfish feed is about 86,000 kJ/kg of fish produced (Troell *et al.* 2004) or more than 100 times the industrial energy input for aeration calculated above. However, direct energy input captures only a part of the energy subsidies for pond aeration. Energy is also required to obtain raw materials, construct, and maintain aeration equipment. These costs are difficult to calculate, but still represent only a small fraction of the overall industrial energy subsidies in intensive pond aquaculture because of the overwhelming energy inputs associated with manufactured feeds.

10.7.2.2 Waste treatment

All aquaculture produces waste and water or land area is required to assimilate or otherwise treat those wastes. It is instructive in this regard to consider the

degree to which aquaculture production systems are open to the environment. In relatively closed production systems, like recirculating aquaculture systems and ponds operated with long hydraulic residence times, significant quantities of waste produced during culture are treated within the facility and there is little external area needed for waste treatment. In contrast, much of the waste produced in flow-through and net-pen culture systems is discharged directly to the environment. The capacity of the external ecosystem to assimilate those wastes may limit aquaculture production either by polluting the surrounding water to the point where animal welfare inside facilities dependent on that water source is endangered ("self-pollution") or by imposed regulatory constraints on the amount of waste that can be discharged. In addition to effects on aquaculture production, waste discharge into public waters may create problems such as transfer of pathogenic organisms, degraded water quality that limits options for use, water treatment costs, and other downstream impacts.

The ecosystem area needed for waste assimilation, expressed as waste treatment area per unit production facility area, varies over at least two orders of magnitude, depending on the type of production system. At one extreme are aquaculture ponds with low to moderate stocking and feeding rates that can, on the basis of inherent waste assimilation capacity, be operated for many years without draining or intentional water exchange to remove wastes. Natural processes described above remove or transform wastes at rates adequate to prevent long-term accumulation of potential pollutants. In theory, no outside ecosystem support area is needed to treat wastes produced during culture and the pond functions as its own waste treatment facility. In practice, ponds must be occasionally drained for renovation and inventory adjustment and some overflow is inevitable during periods of heavy precipitation. Nevertheless, for ponds operated with long hydraulic residence times, more than 90% of the waste organic matter, nitrogen, and phosphorus produced during culture is assimilated inside the pond before water is discharged (Tucker *et al.* 1996).

Internalizing waste treatment imposes a relatively high direct land cost to pond aquaculture and this cost is evident in the large size of pond facilities. Extensive land use is the result of the pond functioning as both an animal confinement area as well as a waste treatment facility. In theory, less than 5% of the pond area is needed to confine fish, meaning that more than 95% of the land and construction costs for ponds can be assigned to waste treatment functions. Effectively this means that the relatively large land area occupied by a pond aquaculture facility is a price the culturist pays for treating wastes on site rather than discharging them to public waters. Engle and Valderrama (2002) explored other costs (such as aeration, labor, etc.) associated with internalizing waste treatment in channel catfish ponds and calculated that almost 30% of the total cost of producing channel catfish can be ascribed to internal waste treatment processes. Land area requirements and other costs resulting from internalizing waste treatment limit profitable pond aquaculture to areas where large tracts of flat land are available at a reasonable price.

Aquaculture production in ponds is therefore limited by the finite capacity of the pond ecosystem to treat wastes produced during culture (Hargreaves &

Tucker 2003). Further intensification of production is possible only if wastes are treated outside the culture unit, usually by discharging wastes to public waters. At that point, the culture system is no longer a pond as defined here, but represents a system that is intermediate between a pond and a flow-through system. Displacing wastes from the pond requires an ecosystem area outside the culture facility for treatment. In that case the cost of treating wastes discharged to public waters is borne by society, not the aquaculturist.

The external ecosystem area needed to treat aquaculture wastes depends on the quality and amount of waste discharged and the hydrology and biology of the ecosystem into which wastes are discharged. Based on the few studies conducted, it appears that areas between 100 and 300 times the facility area are needed to treat wastes produced from intensive cage and net-pen fish culture (see, for example, Berg *et al.* 1996; Kautsky *et al.* 1997; Folke *et al.* 1998; Brummett 1999). Note that these values for the ratio of waste assimilation area to fish-holding area are somewhat larger, but within the same order of magnitude, as the ratio of waste treatment area to fish-holding area in intensive catfish ponds described previously. This is not a coincidence. The same biological and physicochemical processes are responsible for waste treatment whether the water is inside a pond or has been discharged to a lake, stream, or estuary. Therefore, all other things being equal, the area required for treatment of a unit of waste should be of similar magnitude regardless of the degree to which a particular culture system is open to the environment. The difference, of course, is that the ecosystem area needed for waste treatment in ponds is, for the most part, inherent in the production system whereas waste treatment for flow-through systems and net pens is external to the system.

10.8 Consequences of unregulated algal growth

An important characteristic of pond aquaculture is the low level of control over many of the important factors of production. Phytoplankton communities are the dominant ecological feature of aquaculture ponds because their metabolic activities directly or indirectly affect the suitability of the pond environment for growing the crop. Some ponds are fertilized to increase phytoplankton production as the food base for cultured fish. In ponds with feeding, phytoplankton communities develop as the unintentional consequence of applying nutrient-dense feeds. As a practical matter, the abundance and species composition of phytoplankton communities cannot be controlled.

Phytoplankton are simultaneously desirable and undesirable in aquaculture ponds. Some type of plant community is inevitable in ponds and, of the various communities that may develop, phytoplankton does not interfere with fish harvest as do filamentous algae and emergent or floating aquatic plants. Phytoplankton also produce oxygen and play a key role in waste assimilation. However, phytoplankton can be undesirable when biomass becomes excessive or when the community contains species that produce odorous metabolites or toxins. Odorous algal metabolites impart undesirable off-flavors to the edible

portions of cultured animals, thereby affecting product quality and marketability. Algal toxins may kill the cultured animal.

Communities of odorous or toxic algae are called "harmful algal blooms" or HABs. Harmful algal blooms are usually transient in ponds and they develop and then disappear in a seemingly random manner. Environmental factors regulating phytoplankton community composition are understood only at the most basic level (Reynolds 1984). For example, HABs tend to be more frequently encountered in ecosystems with high nutrient loading. Past that generality, predicting the occurrence of odorous or toxic species is impossible and managing the environment to prevent harmful blooms is very difficult.

10.8.1 Off-flavors

The most common off-flavors in pond-raised animals are caused by either geosmin or 2-methylisoborneol (MIB). Geosmin has an earthy odor redolent of a damp basement. MIB has a unique, musty-medicinal odor, somewhat like camphor. Both compounds are essentially nontoxic to plants or animals. They are among the most highly odorous compounds found in nature and are common in aquatic and terrestrial environments—they give soil its characteristic odor, for example. Geosmin and MIB are synthesized by a variety of fungi, actinomycete bacteria, and blue-green algae (cyanobacteria) but in ponds they are nearly always produced by blue-green algae. Off-flavors in aquaculture are reviewed by Tucker (2000).

Relatively few species of blue-green algae synthesize geosmin or MIB, and flavor problems in cultured animals coincide with the development and disappearance of odor-producing species. When odorous species are present, waterborne geosmin or MIB is absorbed by fish or crustaceans across the gills and deposited in tissues throughout the animal. Geosmin and MIB are extremely fat soluble and strongly concentrated from the water into animal tissues. Further, the human sensory threshold for these compounds occurs at low tissue concentrations. Because geosmin and MIB are intensely odorous and highly bioconcentrated from water, they can cause flavor problems in fish or crustaceans when present in water even in trace amounts.

When odor-producing algae disappear from the phytoplankton community, geosmin and MIB in fish or crustacean tissues are purged or metabolized. Rates of depuration depend primarily on water temperature and tissue fat content (Johnsen *et al.* 1996). Lean fish in warm water may completely depurate intense off-flavors within days whereas fatty fish in cold water may remain off-flavor for months.

Off-flavors caused by geosmin or MIB occur in pond-cultured animals throughout the world. Earthy-musty off-flavors have been reported from such widely different species and geographical regions as pond-raised channel catfish in the southeastern United States, rainbow trout (*Oncorhynchus mykiss*) raised in prairie "pothole" lakes in central Canada, common carp (*Cyprinus carpio*) from intensive fish culture ponds in Israel, Atlantic salmon from net-pens in lakes

in Scotland, and penaeid shrimp in low-salinity ponds in Ecuador (summarized in Tucker 2000).

There are strong ecological similarities among waters that routinely produce tainted fish. Nearly all waters commonly producing fish tainted with geosmin or MIB are static, nutrient-enriched freshwaters. In these systems (as exemplified by warmwater aquaculture ponds), blue-green algal blooms are a natural consequence of prevailing environmental conditions and off-flavors are relatively common. Odorous blue-green algae do not thrive in pond water with salinity greater than about 5 ppt, and shrimp or fish cultured in such water seldom, if ever, have taints associated with geosmin or MIB.

The occurrence of odorous blue-green algal blooms is unpredictable and, in pond cultures where off-flavors are common, fish are usually "taste-tested" before harvest. If off-flavors are detected, the crop is not harvested. Development of off-flavors can be a severe economic burden for aquaculturists because it prevents timely crop harvest, increases production costs, disrupts cash flows, and interrupts the orderly flow of fish from farm to processor. Furthermore, if off-flavored fish or crustaceans are inadvertently marketed, the negative reaction of consumers may adversely affect market demand.

Management of off-flavors is difficult and relies upon natural elimination of odorous compounds from flesh to improve flavor quality once fish are no longer in the presence of the organism producing the compound. Fish with off-flavors may be simply held in the pond until odor-producing algae disappear. At times, farmers attempt to expedite the process by treating ponds with algicides to eliminate or reduce the density of odor-producing algae.

10.8.2 Algal toxins

Many species of algae produce toxins that directly or indirectly affect aquaculture. Some toxins reduce the growth of or possibly kill the cultured animal. Other toxin-producing algae indirectly affect aquaculture production when toxins accumulate in the tissues of animals that feed upon the algae and are transmitted through the food chain. Toxins that are passed along the food chain may represent a health threat to humans who consume the product. Toxin-producing algae come from diverse taxonomic groups, including blue-green algae, diatoms, and a variety of flagellated marine and freshwater species of prymnesiophytes, euglenoids, dinoflagellates, and chloromonads. Most toxin-producing algae are marine and are important in shellfish farming or net-pen fish culture in bays and estuaries. Fewer species are important in pond aquaculture (Boyd & Tucker 1998).

Algae-related toxic events in ponds may result when toxin-producing algae are present in the water supply or when toxin-producing populations develop naturally as part of the pond phytoplankton community. Ponds filled with water from estuaries, bays, or other saline water bodies are particularly susceptible to toxic algae events when blooms of toxic dinoflagellates are present in the water supply. The infamous "golden alga" *Prymnesium parvum* occurs worldwide

in warm estuaries and fresh waters with a relatively high mineral content. Populations of *P. parvum* may be pumped into ponds from a water source or populations may develop naturally in ponds of the proper salinity. Certain blue-green algae produce hepatotoxins (liver toxins) or neurotoxins that are toxic to a wide range of vertebrates and invertebrates, especially warm-blooded animals. Populations of toxic blue-green algae develop in freshwater ponds as part of the normal succession of phytoplankton communities.

Fish kills caused by *Prymnesium parvum* have been documented throughout the world and considerable research has been conducted on mechanisms of toxicity and control measures. A website maintained by the Texas Parks and Wildlife Department (www.tpwd.state.tx.us/landwater/water/environconcerns/hab) contains abundant information on the ecology, impacts, and management of *Prymnesium parvum* and other toxic algae. Quite unexpectedly, aside from toxic events related to *Prymnesium,* relatively few fish kills have proven to be caused by algal toxins in aquaculture ponds, despite the high potential for such problems to occur. In many instances, fish kills are caused by dissolved oxygen depletions associated with excessive algal abundance but are mistakenly attributed to algal toxins because of the coincident occurrence of suspected toxin-producing algae. The lack of widespread algae-related toxic events in aquaculture is especially puzzling for blue-green algae because toxin-producing blue-green algal strains are very common in warm, freshwater aquaculture ponds. Further, neurotoxins and hepatotoxins from blue-green algae are quite toxic to fish when injected directly. There is no good explanation for this paradox although several factors may contribute to the apparent tolerance of freshwater fish to blooms of potentially toxic blue-green algae (Boyd & Tucker 1998).

Managing toxic algal blooms is difficult in ponds. When the water supply is the source of toxic algae, careful monitoring of source water may allow the aquaculturist to avoid pumping from the water supply until the toxic bloom disappears. Selecting sites and water sources that are not historically prone to toxic algae blooms may also reduce risk. Once blooms are established in ponds, attempting to eliminate toxin-producing algae by killing them with algicides may make conditions worse because large amounts of toxin will be released into the water when algae die and cells lyse. The dilemma of managing toxic blooms is especially problematic for blue-green algae because toxin-producing strains are common in aquaculture ponds across the world, yet there is little direct evidence of harmful consequences related to toxin production. Furthermore, managing the taxonomic composition of phytoplankton communities in ponds is effectively impossible. The ecology of toxin-producing algae and their potential impacts and management in aquaculture are complex subjects, and additional information can be found in Boyd and Tucker (1998) or at the Texas Parks and Wildlife Department website previously referenced.

10.9 Practical constraints on pond aquaculture production

This chapter's recurrent theme has been that pond aquaculture production is limited by the capacity of ecosystems to provide essential life-support functions.

Overcoming these limiting factors—which progressively shift from food supply to oxygen production to waste removal—requires energy input from outside the pond. At some point, waste treatment capacity is exceeded and production can be increased only by changing the system so that it is functionally no longer a pond—at least as ponds are defined in this chapter. That is, when production is intensified to the point where the pond's waste-treatment capacity is exceeded, water must either be rapidly exchanged (at which point it becomes a flow-through system) or treated in separate units or filters (at which point it becomes a water-recirculating aquaculture system).

In reality, potential aquaculture production is affected by numerous factors unrelated to ecosystem services. At the most basic level, production is affected by factors that affect fish growth and survival. Some of these factors can be controlled by the culturist, but many are not amenable to management control. Those factors act as constraints and result in a situation where potential production is seldom achieved under commercial conditions. In fact, actual production usually falls far short of potential production. This section explains why fish production in ponds always falls below potential by examining the effects of seedstock availability, cropping system selection, and crop losses as practical, production-limiting constraints.

Most factors affecting production are manageable to some degree, although overcoming these constraints may not be practical or economically justified. For example, water temperature is the most important variable affecting animal metabolism and pond ecology, but, as a practical matter, temperature cannot be controlled by the culturist (other than through site selection). Another common example involves the decision to treat infectious diseases by adding a chemical therapeutant to pond water. Therapeutants are greatly diluted when added to ponds, and large amounts of chemical may be required to achieve an effective concentration. In some instances, treating the disease may not be justified economically for commodity fish production.

10.9.1 Seedstock availability

Aquaculture production and profitability can be optimized only when the culturist has complete control of the production cycle. Production should begin with healthy juveniles of the desired size and the production cycle should be initiated when conditions are best for early growth. Most commercial aquaculture relies on controlled reproduction of captive animals. There are, however, important examples of aquaculture relying on wild-caught juveniles for seedstock (Hair *et al.* 2002), although the practice is increasingly discouraged due to potential adverse effects on natural populations.

Timing of aquatic animal reproduction depends on species-specific sets of environmental cues, such as changes in temperature, photoperiod, tides, or moon stages. For some species, such as channel catfish, captive broodstock are allowed to reproduce under conditions that resemble those encountered in the wild. This practice is simple and inexpensive, but supplies of juveniles are seasonal and reproductive success may vary from year to year depending on changes in

weather or other factors. Seasonal availability of seedstock and an uncertain supply can mean that growout strategies (such as initiation of the production cycle) depend more on seedstock availability than on optimizing the temperature-dependent growout process.

Greater control of reproduction can be gained by artificially manipulating the environment to stimulate gametogenesis, often followed by administration of hormones to induce spawning. Complete control over reproduction allows a consistent, year-round supply of seedstock, which is especially important for pond systems with a relatively constant water temperature in which multiple crops can be produced annually or cropping cycles can be staggered. Tilapia are particularly exemplary as the kind of species amenable to this approach. Examples of culture systems that function best when seedstock are available year-round include recirculating systems, flow-through systems with a constant-temperature water supply, and ponds in tropical regions. Year-round spawning is less important and may not be desirable for commercial pond aquaculture in temperate regions. For example, out-of-season spawning is easily induced in brood channel catfish, carps, or other seasonal spawners by manipulating water temperatures in indoor systems. However, for large-scale fingerling production, fish must be moved into ponds for further growth and little advantage is gained by moving fish to ponds when water temperatures are suboptimal.

10.9.2 Cropping system and market demand

For purposes of this discussion, cropping system is defined as the manipulation of stocking density and fish biomass in ponds to maximize the temperature-dependent waste assimilation capacity, often indicated by maximum daily feeding rate. The most common cropping system in ponds is the single batch where one cohort of fish is stocked as fingerlings and grown out to market size. Assuming favorable temperatures for growth at stocking, the production potential of the pond is not achieved at this time because most of the waste assimilation capacity is not used when fish are small. In fact, the carrying capacity of the pond is only achieved for a short period just before harvest. To make better use of production capacity, culturists may manipulate density by splitting the stock periodically during the culture period. The best frequency of stock splitting is a trade-off between gains associated with maximizing carrying capacity and additional labor costs for handling fish. The production-to-capacity (P/C) ratio is the metric that is used to describe use of the pond carrying capacity. It is calculated as production per unit time (usually one year) divided by the theoretical capacity for production. In recirculating aquaculture systems, P/C of 2 to 3 is possible, and indeed are necessary for economic sustainability. In ponds, P/C is always less than one.

In channel catfish farming, the multiple batch production system is used where multiple cohorts of fish are present in the pond at any one time and ponds are not drained for harvest. The system has evolved as a response to the need to meet regular supplier demand for market-size fish and as a hedge against the risk of

off-flavor that prevents timely harvest. Harvest timing in commercial aquaculture is usually dictated by market demands rather than being set to optimize production. These market demands might require a constant supply or an elevated supply during certain times of the year or holidays. Market demand for the products of pond aquaculture rarely corresponds to the end of the growing season, when a single-batch pond would normally be harvested, especially in temperate regions. It is difficult to match market demand with fish production cycles.

Channel catfish processors in the southeastern United States require a year-round fish supply that is met by holding some food-sized fish in ponds throughout the year. In effect, pond space that could be used to produce a new fish crop is used indirectly by the processors to hold fully grown fish in inventory. Farmers attempt to address this processor-imposed harvest schedule by staggering production start dates so that multiple populations reach market size at different times throughout the year. Even if production is staggered to meet processor demands, some harvest-sized fish must be held over winter to meet processor demands for fish in winter and spring. Overwintering harvest-sized catfish to meet winter and early-spring processor demand exposes fish to increased risk of crop loss from infectious disease.

Furthermore, as described in a previous section, algae-related off-flavors are common in pond aquaculture and off-flavored fish are usually not accepted for processing. Similarly fish may not be accepted for harvest and processing during periods of temporary oversupply. In either case, fish must be held past optimum harvest time, which increases risk of loss and reduces long-term productivity.

Because specific growth rate and feed conversion decrease as fish get larger, the production cycle should end when fish reach the desired market size. Growing fish past that point extends production cycle duration, worsens feed conversion, and increases the risk of crop loss to disease or predators. Production cycle planning should also minimize intervals between crops when the pond is empty and unproductive.

10.9.3 Crop loss

Crop loss to disease and predation affects production and profitability in all types of agriculture. Losses can be particularly troublesome in pond aquaculture because it is exceedingly difficult to make ponds biosecure. Commercial aquaculture ponds are relatively large outdoor systems that are difficult or practically impossible to disinfect between crops. Ponds are accessible to, or easily colonized by, a variety of disease vectors including mammals, birds, and invertebrates. Pond facilities are often located in rural or isolated areas that support diverse and abundant wildlife and, relative to other aquaculture production systems, ponds are especially vulnerable to wildlife depredations. The isolated nature of pond facilities also makes them an attractive target for poaching.

Morbidity and mortality from disease epizootics and crop loss to predation and poaching are manageable to varying degrees. The degree of management

possible depends on culture species, types of diseases encountered, the availability of management tools (such as vaccines or medicated feeds), facility size, hydrology, and other considerations. The degree to which crop loss can (or should) be managed has an obvious economic component. Ornamental fish and other high-value crops may justify extreme measures such exclusion structures to prevent predator access, surveillance and security measures to prevent poaching, disinfection of source water, disinfection of pond muds between crops, and use of expensive therapeutants or drugs. Such measures may not be cost-effective—or even possible—for lower-value commodity fish crops.

10.9.4 An example using channel catfish pond aquaculture

The impact of practical constraints on the productivity of pond aquaculture has been estimated using data from commercial catfish aquaculture in the southeastern United States (Tucker 2005). Assuming that adequate aeration is available to overcome oxygen supply limitations, potential production is defined by the effects of water temperature on catfish metabolism when water temperatures are below about 20°C and by the nitrogen assimilation capacity of the pond when water temperatures are warmer. Based on those two initial constraints, maximum annual net fish production under climatic conditions in the region is approximately 19,000 kg/ha, which corresponds to the range for maximum production in table 10.1.

The simple model used by Tucker (2005) estimated the crop yield reduction due to the combined effects of market constraints (off-flavors and the need for a year-round fish supply), infectious disease losses, and bird predation. The model also estimated the effects of dissolved oxygen limitation on fish growth. Although an initial assumption of the model was that adequate aeration is available to overcome oxygen supply limitations, commercial catfish ponds seldom have adequate aeration to provide non-limiting oxygen supplies. Combined, these factors reduce annual yields by 60% to 7,500 kg/ha. Although the model is a vast oversimplification of actual conditions, the estimated annual yield under commercial conditions is in the range of yields reported by farmers in the southeastern United States.

This exercise has significant implications. Catfish production could be increased 25 to 50% by improving fish health management, reducing predator loss, and managing fish flavor quality so that market-sized fish are promptly removed from ponds. Significant progress toward that goal can be made by properly implementing current technologies. Greater improvement in yields will depend on overcoming limitations of current aeration technology, such as using some variation of the partitioned aquaculture system (chapter 13).

10.10 Comparative economics of culture systems

Comparing economic performance among culture systems is difficult because economic sustainability is more strongly related to operational characteristics

that apply universally to culture systems. Although market demand, product price, and feed cost are critical external aspects of economic sustainability, site selection is the most important operational characteristic affecting potential success. Physical site characteristics have a strong deterministic effect on selection of culture system and ultimate system performance. For example, selecting a pond culture system is a rational economic decision where there are large areas of flat, low-cost land with abundant water resources. For ponds, physical characteristics like soil type, topography, hydrology, and climate are basic aspects of site selection. The environmental variables that affect production vary by species but temperature is universally important as the main factor controlling metabolic rate. Control of temperature at levels optimum for aquatic animal growth is seldom practical or cost-effective, which is especially true in ponds. Climate is a key site selection criterion that determines the maximum growth potential of cultured animals and the productive potential of a site.

For any aquaculture operation, choosing the appropriate scale of production is a decision rivaled in importance only by site selection. A production scale that is too small restricts marketing options and a production scale that is too large often means that fixed costs, especially the cost to borrow capital (indicated by debt-to-equity ratio), are too large. Irrespective of culture system type, a small-scale operation can be profitable with a niche or targeted market for high-value products. A large-scale operation can be profitable by achieving economies of scale on inputs associated with large size and marketing products as a relatively low-value commodity. As a commodity, seafood competes with other sources of animal protein, especially poultry, in the market. Worldwide, nearly all commodity fish for domestic consumption are produced in ponds.

All aquaculture operations must have access to basic natural resources (land, water, and energy), capital resources, and human resources (labor). Selection of appropriate culture systems also depends on the availability of physical infrastructure and access to science, technology, and information infrastructure. Economic performance will depend on how resource inputs and infrastructure are combined and applied in production, the cost of the inputs, and how products are marketed (Shang 1990). Net revenue is generally most sensitive to market price of product and unit feed costs. In general, pond aquaculture is favored where land-use intensity and cost is low and water resources are abundant. Increasing land value and water scarcity favors intensification of pond culture.

With pond aquaculture, unlike other production systems, a wide range of culture system intensity is possible. For example, flow-through and recirculating systems are entirely dependent on external food supplies but ponds are dependent on external food supplies to a variable degree, largely as a function of culture system intensity. As culture system intensity increases, the dependence on externally provided inputs, especially manufactured feed, increases. The proportion of variable costs represented by feed increases with culture intensity. However, variable costs per unit production in intensive systems are potentially lower because of increased control over the factors that affect growth and survival, especially feeding.

Across all culture systems, managing production capacity of the culture unit is critical to good performance. Examples of cropping systems that can increase the ratio of production to carrying capacity include manipulation of stocking density as a function of size, stocking multiple cohorts, and partially harvesting the population followed by another stocking. Growth and survival can be increased by fertilization, feeding, water quality management, and disease and predator control.

A common management goal among production systems is to increase efficiency and reduce waste. Efficiency indicators can be used to evaluate system performance as a function of major resource inputs, such as energy, land, water, and feed. However, comparing efficiency indicators across culture systems can result in misleading conclusions. For example, production per unit land area in pond aquaculture is much less than inherently intensive systems like cages, raceways, or recirculating systems. A better comparison would consider performance in relation to the factors of production that are most limiting, and therefore most valuable, in a particular location. More broadly, considering the additional area required for the production of feed ingredients and waste treatment tends to overwhelm a land-use efficiency indicator based solely on the land area occupied by a particular facility.

Other than comparing specific efficiency measures, broad qualitative statements can be made about the comparative economic performance of different culture systems. In this context it is useful to consider the economic dimensions of culture systems with respect to food supply and life support.

Food supply is the essential service with the greatest economic implications, one that transcends the diversity of culture systems as a concern. Given that feed represents from 30 to 60% of variable costs in semi-intensive or intensive pond aquaculture, economic performance is strongly dependent on improving feed conversion or reducing feed cost per unit production. In some cases the cost-benefit ratio favors pond production systems where cultured animals are fed; in other situations, more traditional, low-input or fertilized systems are favored.

Providing oxygen to cultured animals is an essential life-support service. In ponds, oxygen is mainly provided by algal photosynthesis. Supplementation of the oxygen supply by aeration, circulation, or water exchange has a cost. In the context of the collective magnitude of the three main cost items (feed, seed, and labor), such a cost increase is often justified by the potential benefit. Obviously the availability of reliable power supplies is a prerequisite for the supplementation of oxygen supplies by aeration.

Fundamentally waste from a culture system can be treated within the farm or facility or outside a farm or facility, or sometimes both. Where waste is treated outside the farm or facility, those costs are borne by society and are considered an externality of production. Where waste is treated inside the farm or facility, those costs are internalized and borne by the farm owner. Given that the most important aspects of economic sustainability are independent of the culture system, ponds have two potential economic advantages relative to other culture systems. To a degree dependent on the food habits of cultured species, production in ponds based on fertilization to produce natural food items may

have a high benefit to cost ratio. Internalizing waste treatment represents an additional operating cost compared to culture systems where waste treatment takes place external to the farm or facility. However, if ponds are operated within the waste assimilation capacity, the operating cost of waste treatment is essentially free. Furthermore, treating as much waste as possible internal to the farm or facility is responsible aquaculture. The often-lengthy process of permitting aquaculture facilities that release waste to public waters can increase production costs due to attention to regulatory matters or litigation.

10.11 Sustainability issues

Although there is no consensus on a functional definition of sustainability, the concept is understood to encompass the intersection of three overlapping domains: economic, environmental, and social. Sustainability implies continuity of production, efficiency of resource use, and responsibility to the welfare of the supporting environment, cultured animals, farm workers, fish consumers, and the broader society. Many of the important environmental and social impacts in aquaculture are independent of culture system. The previous section discussed elements of economic sustainability; here we describe the interrelated environmental and social aspects of sustainability issues that have particular relevance to pond aquaculture, especially those relating to site selection, land use, and property rights.

An underlying theme of this chapter has been that the size of the ecological footprint (an index of sustainability) in pond aquaculture ranges widely. Pond aquaculture extends from nearly self-sufficient production systems with few external inputs to relatively intensive systems relying on large external subsidies such as manufactured feeds, mechanical aeration, and water exchange for waste management. Water-use efficiency in pond aquaculture also varies greatly, with some types having the highest consumptive water use per unit production of all other forms of aquaculture. On the other hand, most ponds are relatively closed systems with an indirect or intermittent hydrological connection to outside water bodies. When pond aquaculture facilities are properly sited, issues such as waste loading, pathogen transmission, and escape of animals from culture units are usually less important for ponds than for culture systems more open to the environment, such as net-pens and flow-through raceways. Of course, the relative risk of those impacts increases as hydraulic retention time of ponds decreases (that is, as ponds become more open to the environment with respect to hydrological connection).

Overall, ponds have a greater range of potential environmental impacts than other aquaculture systems. The relative importance of specific impacts of pond aquaculture depends upon, among others:

- culture intensity
- production scale
- trophic level of species cultured

- hydrological pond type
- local hydrology and climate
- type and scale of local human activities
- extent or concentration of local aquaculture development
- functional integrity and resilience of downstream aquatic ecosystems.

The extraordinary diversity of potential environmental effects makes it impossible to assess the overall environmental performance of pond aquaculture and compile a simple list of impacts. Boyd *et al.* (2007) propose several quantitative indicators of resource use and waste production for aquaculture and provide examples of relative environmental performance of different aquaculture systems. However, it is not possible to develop an overall index of resource use efficiency and waste production by species, production method, or facility. Further details of environmental impacts of aquaculture and their management are discussed in Tucker and Hargreaves (2008). Many environmental and social impacts of aquaculture can be avoided or minimized by implementing better management practices at the farm level, especially those related to site selection.

Different pond production systems may perform well in one area of potential impact but less well in others. For example, channel catfish ponds in the southeastern United States can be operated for many years with very little discharge, so impacts related to waste loading and pollution are low. However, catfish ponds using groundwater supplies may have significant negative impacts related to aquifer overdraft. Which issue is more important? Do the benefits of one cancel the liabilities of the other? Answers to these two simple questions depend on assessing impacts in a more general context than simply quantifying resource use or waste loading. Answers also depend on values, perceptions, and, to an increasing extent, the outcome of public participation in stakeholder consultations. Further confounding these simple questions, there is no consensus on the most serious impacts of aquaculture. Issues such as water pollution, animal escape, pathogen transmission, excessive use of fish meal in manufactured feeds, and land use have all been proposed as serious concerns for one sector of aquaculture or another.

Pond facilities use large land areas compared with other productions systems, so issues such as habitat conversion and land-use conflicts are more frequently encountered in pond aquaculture than in other forms of aquaculture, especially in the coastal zone. At the core of land-use conflicts are disputes between land owners and others over equitable distribution of the costs and benefits of private aquaculture and the fairness of using public resources for private gain. The benefits of private aquaculture often accrue solely to the entrepreneur but in some situations some of the costs of production (such as waste treatment in ponds operated with water exchange) are borne by society, with the potential to reduce public welfare through ecosystem damage and pollution of water resources. Responsible aquaculture means internalizing such costs to the greatest extent.

Perhaps the most prominent example of land-use conflicts in aquaculture is the conversion of mangrove forests to large tracts of coastal aquaculture ponds,

primarily for the culture of penaeid shrimp. It is one of the most contentious environmental and social issues in aquaculture (Boyd 2002). The location of aquaculture ponds in the coastal zone can restrict access to the shoreline and to resources that are traditionally considered to be open access or common property. Numerous instances of conflict, rising to the point of violence, between coastal shrimp farmers and small-scale fishers have occurred. Land- and water-use conflicts also occur between shrimp farmers and crop farmers. The discharge of saline water from inland shrimp farming into irrigation canals can cause local soil salination and reduce the capacity of adjacent lands to grow crops. In some areas, pond aquaculture competes for limited supplies of freshwater with other uses, including for irrigated agriculture, industry, and household use. At the most basic level, land-use conflicts are more common for pond aquaculture simply because they use more land. Ponds are the most commonly used aquaculture system and individual facilities occupy a greater land area than more intensive systems. Proper siting, using selection criteria that transcend basic physical attributes, can often prevent most of the problems that lead to land-use conflicts.

Decisions on land use do not necessarily have to favor one use over another, but pond aquaculture may be relatively advantageous in certain sites. For example, large expanses of land are used for catfish aquaculture in the southeastern United States but those soils are poorly suited for most row crops and their use in aquaculture does not therefore compete directly with other agricultural uses. Pond aquaculture is often possible on marginal or degraded land, such as areas with salinized soils that are not suitable for terrestrial agriculture.

Using fish meal derived from pelagic marine fish in feeds for other fish is another contentious issue in aquaculture. Some believe that culture of certain fish or crustaceans using fish meal in feeds does not contribute to a net increase in global fish production (Naylor & Burke 2005). That is, each kilogram of fish produced in aquaculture consumes more than one kilogram of small pelagic marine fish in the form of fish meal. Others argue that this analysis is flawed and overly simplistic (Tidwell & Allan 2002). Regardless, the point here is that feeds used to grow certain species of animals in ponds have higher levels of fish meal than others, and, correspondingly, the impacts (real or perceived) vary depending on the trophic level of the species in question rather than on which culture system is used to raise the animal. The fish feed equivalence (FFE) can be used to determine the net impact on global fish supplies (Boyd *et al.* 2007). The FFE is a unitless ratio of the weight of pelagic marine "feed fish" needed to produce 1 kg of cultured animal. The FFE for pond-raised channel catfish is 0.2, indicating that the weight of fish used in the feed is much less than the weight of fish produced in culture. The FFE for pond-raised black tiger prawns (*Peneaus monodon*) is 1.7, meaning that the weight of feed fish used in shrimp diets is greater than the weight of shrimp produced. Based on these two examples, some argue that culture of tiger prawns has a greater negative impact on world seafood supplies than catfish farming, even though both are grown in ponds. Most fish grown in pond culture worldwide feed at low trophic levels and therefore contribute to a net increase in global fish supplies. However,

increasingly more fish meal is being used in diets for omnivorous carps, especially in China, as culturists there intensify production.

Most small-scale aquaculturists in the world produce fish in ponds. Small-scale pond aquaculture has many positive social benefits, including increased employment, protein supply, food security, and economic diversification. Pond aquaculture can function as the nexus for economic development and poverty alleviation in rural areas (Edwards *et al.* 2002). Producing fish in pond aquaculture is more labor intensive than in other production systems. Pond aquaculture, as practiced in most of the world, is technologically basic and simple, thereby providing employment opportunities for participation of poor unskilled laborers. However, this attribute highlights the need to protect workers with labor and safety standards.

There are at least three ways to address the environmental and social impacts of pond aquaculture (FAO 2006a). First, the costs of maintaining environmental quality should be internalized to the production system. In pond aquaculture, these costs are internalized to a variable degree but most ponds are operated as static-water systems, which function to internalize essentially all waste treatment costs. Second, impacts can be addressed by adopting better management practices. Although there is some overlap, there are better management practices for each culture system (Tucker & Hargreaves 2008). In pond aquaculture, practices related to site selection and pond construction are particularly important. Finally, impacts can be addressed by integrating aquaculture into development and land management programs, including coastal zone management. Nearly all rural aquaculture is conducted in ponds, and incorporating aquaculture into planning and implementation of development programs can help reduce rural poverty.

10.12 Trends and research needs

Predicting the future of pond aquaculture is difficult because of rapidly changing global economics that will influence the profitability of aquaculture generally. Also, pond aquaculture, which can be an elegant way to grow food with respect to the ecological footprint for food production and waste treatment, uses large tracts of land for the facility and is a large consumptive user of water, relative to other aquaculture systems. As land and water resources become limiting or find more favored alternative uses, pond aquaculture may become a less desirable way of growing aquatic animals. Pond aquaculture will undoubtedly continue to expand as the most economical method of producing certain species, but it will probably contribute a smaller proportion of overall aquaculture production than it did in the past.

Increasing the fisheries supply from pond aquaculture can occur by increasing pond area or increasing the productivity of existing ponds. Expansion of the area of pond aquaculture will continue to be constrained by the availability of suitable sites and competition for arable land with other uses. Construction of additional

ponds is likely to occur on more marginal land and other sites that are not ideally suited for pond aquaculture. Increasing productivity of existing ponds (intensification) is driven by the high levels of human appropriation of existing freshwater resources and chronic water shortages in some aquaculture producing areas. Intensification of pond aquaculture will require additional subsidies of industrial energy to support higher levels of dependence on externally supplied food and enhancement of internal waste treatment processes.

Nutrient budgets for aquaculture systems where animals are fed indicate that 25 to 30% of the nutrients and organic matter in the form of feed is removed at harvest. Given the importance of manufactured feed as the principal cost item, the 70 to 75% of nutrients and organic matter released to the pond environment represents a potential source of revenue if they can be recovered in cultured animals or other economically valuable products. Unfortunately, ponds function to "treat" wastes and present few opportunities for waste recovery and recycling. New pond designs, such as the partitioned aquaculture system or other compartmentalized pond systems, offer opportunities to recover waste nutrients that conventional ponds do not have. Another approach is to recover waste nutrients in microbial biomass or detrital aggregates by adding a source of organic carbon to pond water (Hargreaves 2006; Crab *et al.* 2007). One drawback of this approach is that effectiveness depends on the inputs of industrial energy in the form of aeration to maintain well-mixed conditions.

Small-scale pond aquaculture for the production of fish at low trophic levels for direct consumption or local marketing is widespread in developing countries, especially in Asia. Many are operated as components of traditional farming systems where wastes from one subsystem are a resource for another subsystem. These integrated production systems are well adapted to local conditions and define a benchmark for sustainable aquaculture. Increasing pressures on land and water resources to be more productive suggests that some intensification of traditional systems in lesser-developed countries is also necessary. The goal will be to combine traditional and scientific knowledge, and the judicious use of the most limiting biophysical resources, to increase the productivity and production efficiency of traditional pond systems.

Finally, one recent trend worth noting is the proliferation of product certification efforts. In the context of pond aquaculture, there is great interest in developing ecolabeling programs for sustainable or responsible production of penaeid shrimp and certain fish species in ponds. Many in the environmental community view ecolabeling as an approach to achieve environmental protection and conservation goals, particularly with respect to coastal wetlands. Producers view the label as an opportunity to obtain a price premium for certified shrimp and fish and reduce the environmental and social costs associated with production. Ecolabels have been proliferating but it remains to be seen if consumer demand for these products will be sufficient to change producer behavior and warrant continuing certification efforts. It is also unclear if small-scale producers in developing countries will be able to access the potential benefits associated with ecolabeling.

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